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INTERNAL TRIGGERING MARX GENERATOR USING HYDROGEN THYRATRONS.(U)
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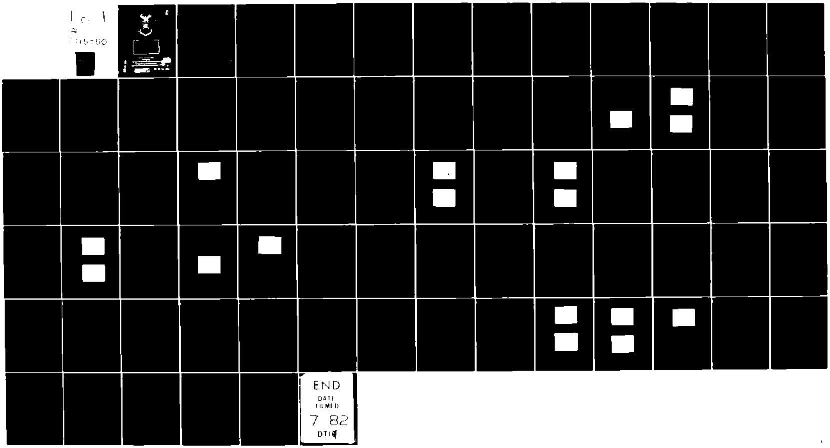

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INTERNAL TRIGGERING MARX GENERATOR
USING HYDROGEN THYRATRONS

THESIS

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AFIT/GE/EE/81D-31

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THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

by

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Graduate Electrical Engineering

December 1981

Preface

This study was an investigation to find a method of triggering thyratrons, when used in a Marx generator, with emphasis on deriving the upper stage thyratrons' trigger signals from the erecting Marx. A successful method was found and the developed trigger timing diagnostics should prove useful to anyone doing research on this topic.

The experiments were conducted at the Pulse Power Technology Branch, Beam, Plasma, and Display Division, U. S. Army Electronics Research and Development Command (ERADCOM), Evans Area Test Facility, Fort Monmouth, New Jersey, with funds provided by ERADCOM and Defense Nuclear Agency.

We would like to express our deep gratitude to our thesis advisor, Mr. William Wright. His guidance, encouragement and ability to nudge our research in the right direction made this thesis successful. Our sincere thanks must also be given to Mr. Sol Schneider, Adjunct Professor for Southeastern Center for Electrical Engineering Education who shared his extensive knowledge of thyratrons with us, along with Mr. Joseph Tomaini and Mr. Robert Burtis who helped us in every way possible.

Special acknowledgement is due to Captain Frederick C. Brockhurst, our professor and studies advisor, who arranged for thesis funding.

Last, but not least, we would like to thank our wives and children for their support and encouragement in completing a very demanding program of study.

Craig L. Kimberlin
Randy L. Lundberg

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Glossary of Terms

Anode Voltage Spike: The magnitude of the spike is measured from the d.c. pre-conduction anode voltage to the peak of the spike on the anode.

Internal Triggering: Firing at least one stage in the Marx from an event in a preceding stage.

Manual Triggering: Firing thyratrons in the Marx from independent grid drivers external to the Marx.

Time Between Anode Falls: Time between the middle of the initial anode voltage fall of a thyratron to the middle of the initial fall of another tube.

Time to Major Break: Time from the 10% point (same as the 10% point on the 10-90% risetime) of the risetime to where the knee on the major rise occurs. This time is used to indicate the sharpness of the initial rise.

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Abstract

Operation of a Marx generator using hydrogen thyratrons as switches, with the switches in the upper stages of the Marx being triggered by a signal derived from the lower stages (internal triggering) was investigated.

The Marx was in a negative output configuration and utilized pulse forming networks (PFN's) as the energy storage elements. Triode, 8613, thyratrons were used along with 175 nanosecond risetime, five section, E-star (E*) configured PFN's.

Timing requirements and erection diagnostics were determined using a two-stage Marx, with both stages triggered from separate external sources (manual triggering). It was found improper timing led to large voltage spikes on the last stage anode and a poor output pulse shape. An attempt to trigger the second (N+1) stage from a signal in the first (Nth) stage was unsuccessful because of long tube turn-on times.

A three-stage Marx was examined, with all stages triggered manually, to confirm timing requirements. Triggering the third (N+2) stage from a signal in the first (Nth) stage, with stages one and two externally triggered, was successful.

Triggering the N+2 stage from the Nth stage using a four-stage Marx (four from two and three from one) was very successful.

The investigation showed the amplitude of the voltage spike, on the last stage anode, and the output pulse shape to be a function of the trigger timing between stages. Output pulse risetime was about 57% of the PFN's risetime.

It is recommended that future work in this area look at the effects of using PFN's with faster risetimes.

I. Introduction

Background

Power supplies to drive loads such as high energy lasers, charged particle beam accelerators or electron beam guns require repetitive operation in the kilohertz (kHz) range. Marx generators are commonly used to provide high energy power for various loads.

Basic Marx generators operate by charging capacitive energy storage elements arranged in parallel to a low or medium voltage level. Switches are used to electrically reconfigure (erect) the storage elements in series, producing an effective multiplication of the charging voltage (Ref 1: 494).

The sequence of operation for a Marx generator using pulse forming networks (PFN's) for storage elements is shown in Figure 1. The charging impedances (Z) are chosen to appear as short circuits during charging of the PFN's and act as open circuits during the discharge of the PFN's.

The switching component normally used with the Marx, a high pressure spark gap, is severely limited in repetition frequency by the time required to recover its voltage holdoff capability for the next charging cycle. The thyratron, a low pressure, gas filled, hot cathode switch is inherently capable of much higher repetition frequencies. Since thyratrons are switched differently than spark gaps, they will not substitute directly for the spark gaps.

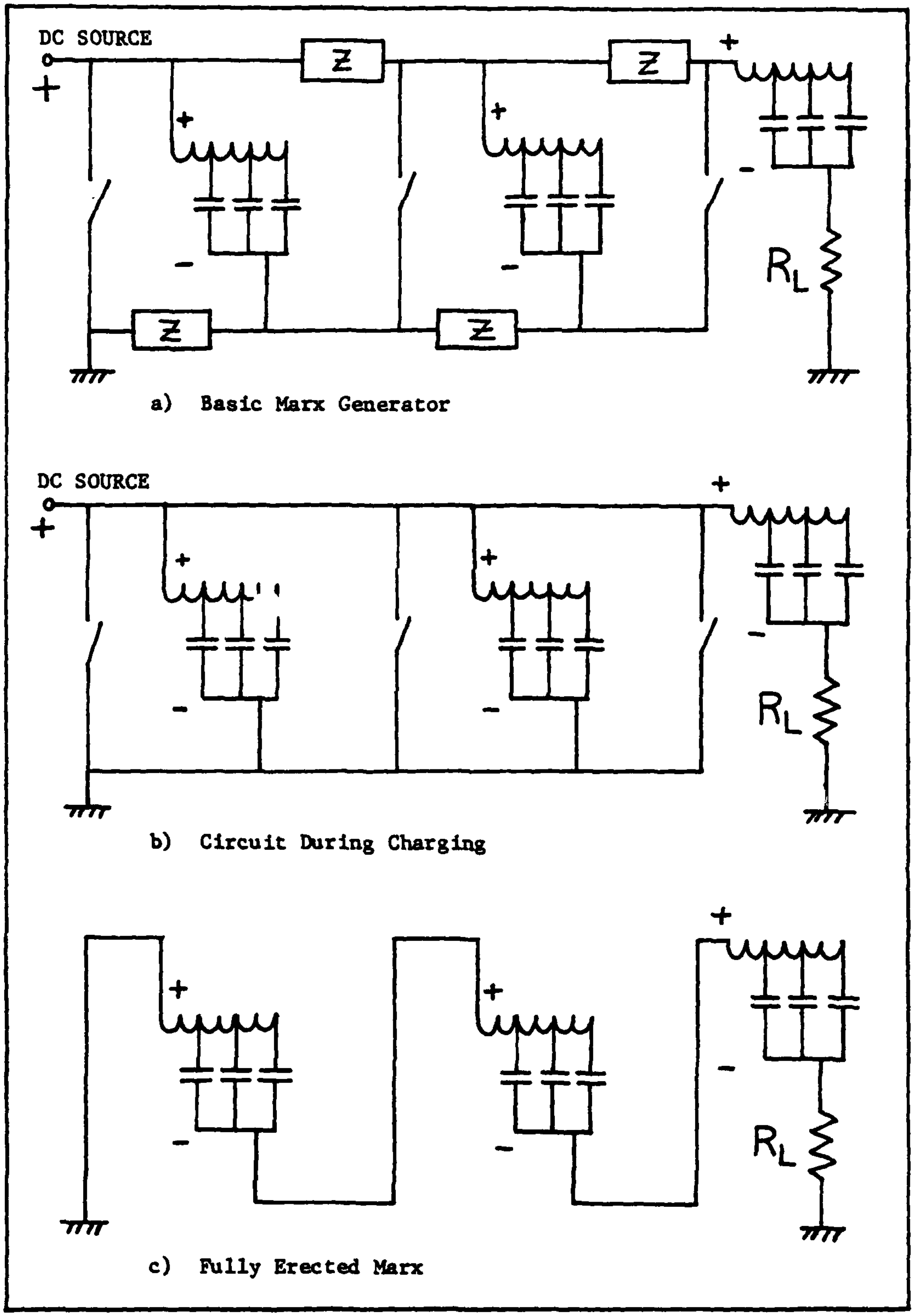

Figure 1. Marx Generator Operation

The use of thyratrons in a Marx has been prevented by the requirements to introduce a trigger signal and heater power to the thyratron at elevated voltage levels. Isolation of these inputs at high voltages is a very serious problem.

Thyratrons are normally switched on when a grid pulse is applied, but will also go into conduction if their breakdown voltage is exceeded. Conduction due to self-breakdown (overvolting) is undesirable since it results in slower deionization times, decreased lifetimes at higher frequencies and a loss of control over timing of the switching event. Proper operation of the thyratron requires the grid pulse be applied soon enough to allow the start of conduction before overvolting occurs.

Marx operation imposes an additional requirement on the switching of the thyratron. A well formed output pulse requires the Marx be erected in an orderly manner. A poorly formed output pulse results from applying the grid pulses too early or too late.

A logical method to obtain the grid pulse and grid pulse timing signals for the upper stage thyratrons would be to derive them from the lower stages of the Marx. Determining how to achieve this method could lead to a simple, low cost triggering scheme.

Problem

Develop an internal triggering scheme for thyratrons employed in a Marx generator with the following requirements:

1. The grid pulses and timing are to be derived from the erecting Marx itself.

2. The thyratrons must not be fired by overvolting.

3. The Marx must produce a good output pulse shape.

4. The triggering scheme should allow the Marx to use any number of stages.

Scope

The study was limited as follows:

1. Only PFN's were used as the energy storage elements.

2. Only the negative output Marx configuration shown in Figure 2 was used. A study on various types of Marx construction was not conducted.

3. No experiments or recommendations regarding tube types were made. The only thyratron employed was the 8613/HY1A triode.

4. Basic isolation transformer techniques were used to supply heater power to the thyratrons. Isolation of the heater power supply at higher voltages was not addressed.

Assumptions

The following assumptions were made at the beginning of the investigation:

1. Adequate energy is stored in each section of the Marx to fire a following stage, without adversely affecting the output of the generator.

2. Use of isolation transformers to supply heater power will not affect the triggering properties of the thyratrons.

Method of Evaluating Results

The internal trigger scheme was considered to be operating properly if two conditions were met:

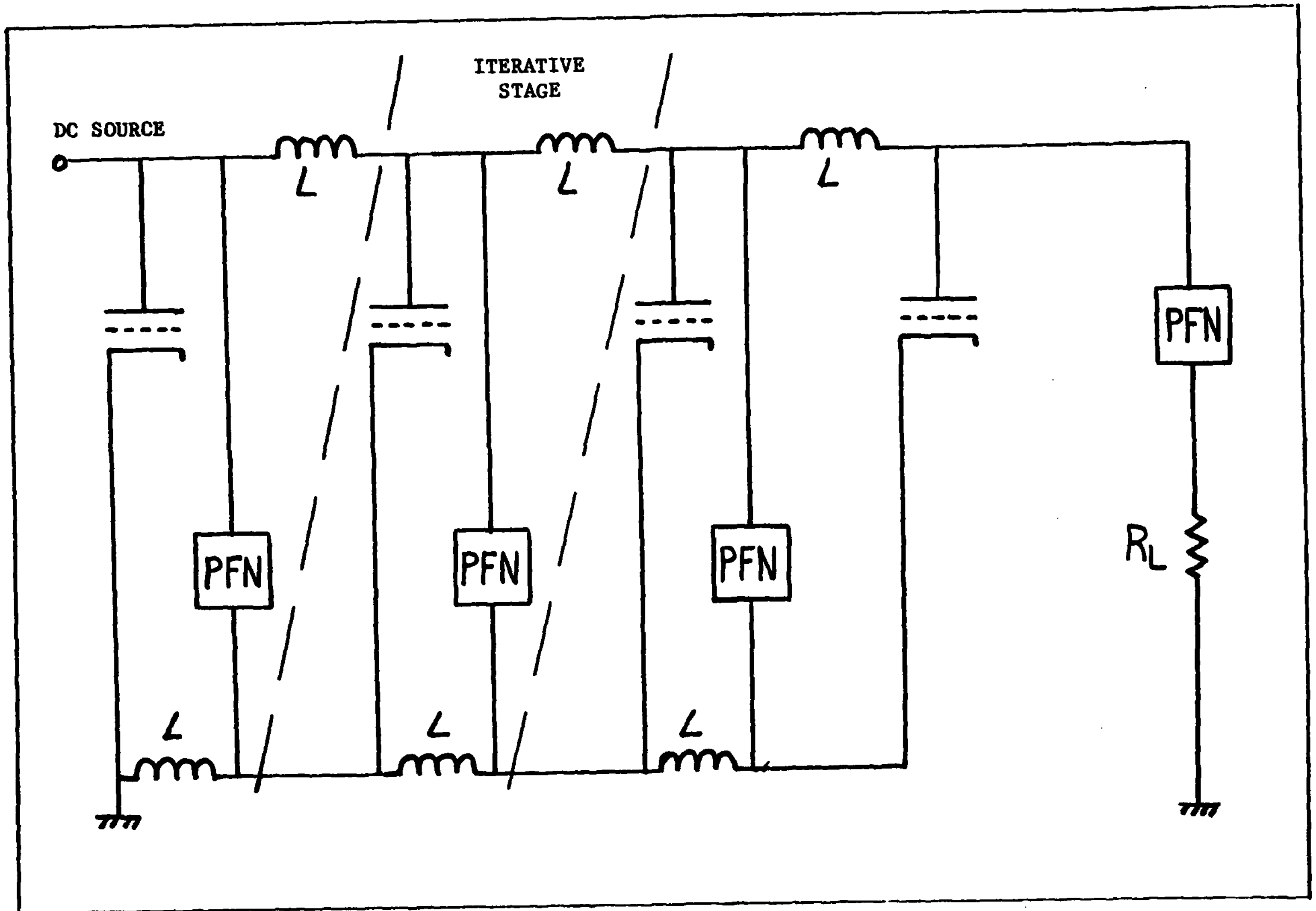

Figure 2. Negative Output Marx Generator

1. Excessive anode voltage spikes on the upper stage thyratrons did not occur. When the tubes are operating near breakdown voltage a large spike will cause the thyratron to fire from overvolting which is undesirable.

2. The output pulse shape had a fairly smooth rise on the leading edge and the top of the pulse was relatively flat and free of large oscillations.

These conditions, especially the second, are a judgement call because what is flat or smooth to one person may not be to the next. The anode voltage spike was deemed excessive above 2,000 volts, for the 8613, since a larger spike means a lower operating voltage for the thyratron.

Instrumentation for measurements was done with a Textronic 7834 oscilloscope, Textronic (6015) high voltage probes and Pearson Electronics Wide Band Pulse Current Transformers, Model 110. When oscilloscope tracings are shown, the word "division" always refers to small (.5 cm) squares.

<u>Approach and Presentation</u>

The thesis is divided into four main chapters with supporting appendices.

Chapter II covers the two-stage Marx generator. Manual triggering is looked at first to determine timing requirements and develop erection diagnostics. Internal triggering is then investigated and results given.

Chapter III covers the three-stage Marx. Manual triggering is examined again to determine differences between two and three-stage operation. Internal triggering is then accomplished and results given.

Chapter IV covers the four-stage Marx. Only internal triggering is investigated and results given.

Chapter V presents conclusions and recommendations.

II. Two-Stage Marx Generator

Introduction

This chapter presents experimental results for a two-stage Marx generator.

Manual triggering is covered in the first half. A complete description of the Marx circuit and the operating conditions are given. Effects of various trigger delays are presented and a set of diagnostics is derived to evaluate results for internal triggering.

Internal triggering is covered in the last part. The trigger circuit utilized is described and its anticipated operation is discussed. Results of an attempt to fire the second (N+1) stage from the first (Nth) stage are given.

Manual Triggering

Both thyratrons of a two-stage Marx were externally triggered to determine the timing requirements necessary to prevent excessive anode voltage spikes and to observe output waveforms for various time delays between tubes one and two. The time difference between firings is measured from the anode voltage falls of the tubes. Anode falls are used for this measurement because they always show when the tubes are beginning to conduct, which isn't always observable when looking at grid currents or voltages.

Circuit and Component Description. A manually triggered negative output two-stage Marx was set up as shown in Figure 3. A 16 kilovolt (kV), 400 milliampere (mA) direct current (dc) power supply was used to charge the PFN's.

The switch tubes are 8613/HY1A, 20 kV, 500 amp (A) triode hydrogen thyratrons produced by EG & G. A listing of the manufacturer's specifications is provided in Appendix A. Heater power was supplied by low capacitance isolation transformers.

Stage isolating chokes (L) consist of 1.7 millihenry (mH) inductances without mutual coupling.

Each PFN is a five section E* configuration with a 50 ohm characteristic impedance, 1 microsecond (μs) pulse width and a (IEEE) risetime of 175 nanoseconds (ns). Time to major break (see definitions in glossary) is also 175 ns.

Pulse transformer T_1 has a 1:1 turns ratio and provides isolation for the second stage trigger source from the elevated voltages that appear on tube two.

EG & G, TM-27 Thyratron Drivers provide the trigger sources for the tubes. The trigger circuit was arranged so each thyratron could be fired independently with any desired time delay between the two.

The load resistance consisted of two tubular, low inductance, carborundum resistors with a total resistance of 94.4 ohms.

Operating Conditions. Heater voltages were set to a mid-range value of 6.3 volts RMS on both tubes. The peak anode voltage, e_{py}, was set to 6 kV, measured at the anode of the first thyratron. The repetition rate was 100 Hertz (Hz).

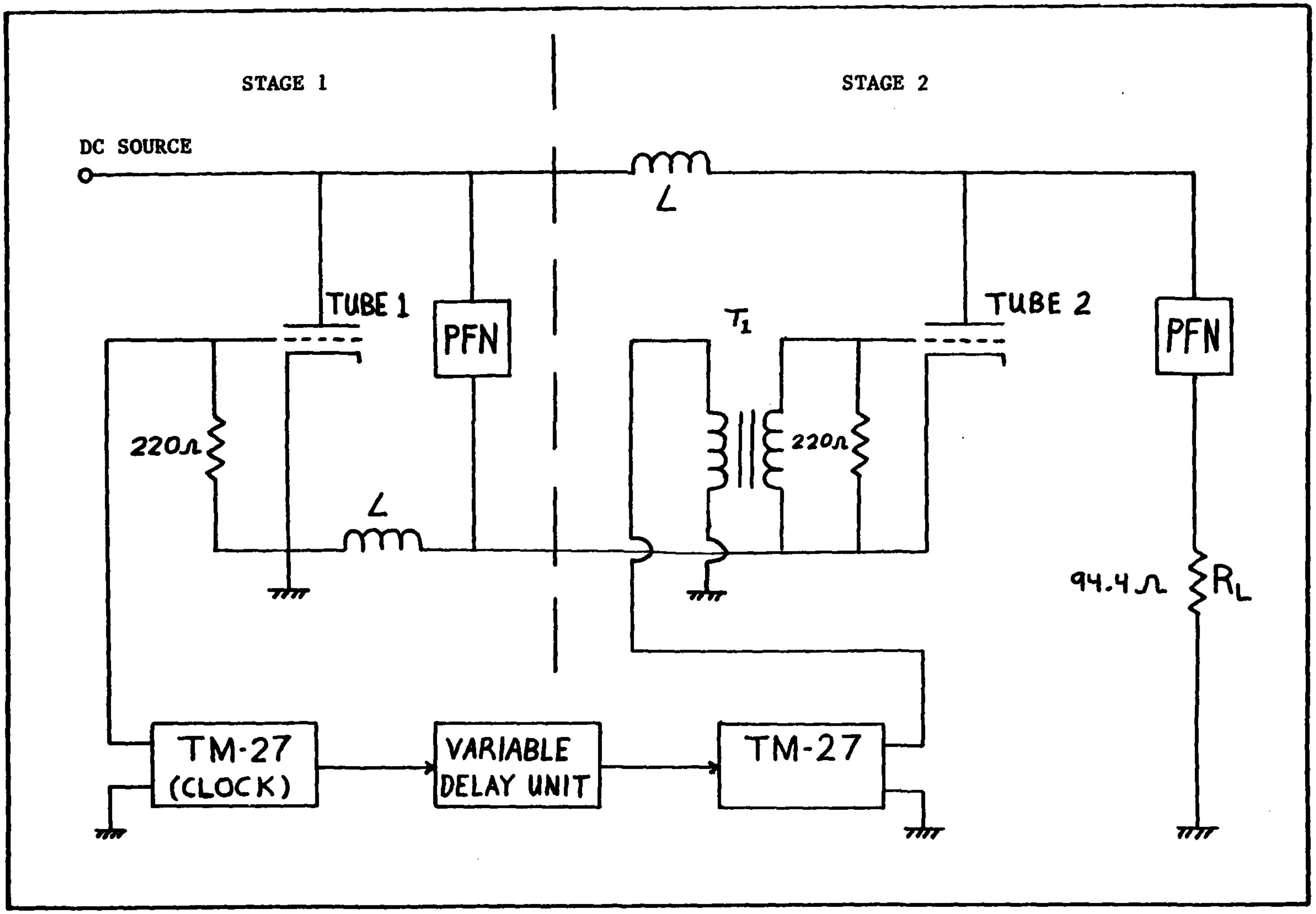

Figure 3. Manually Triggered Two-Stage Marx

Results. The effects of varying trigger timing are illustrated in Figures 4, 5 and 6. Figure 4 shows three traces of tube one's anode voltage for different trigger timing and Figure 5 shows three traces of tube two's anode voltage for different timings. Load voltages for the different timings are shown in Figure 6. The top traces show the anode and load voltages when tube two is firing before tube one. Middle traces show the anode and load voltages for the best load shape obtainable. The bottom traces show the anode and load voltages when tube one is firing before tube two. The three traces in each figure are independent vertically and horizontally.

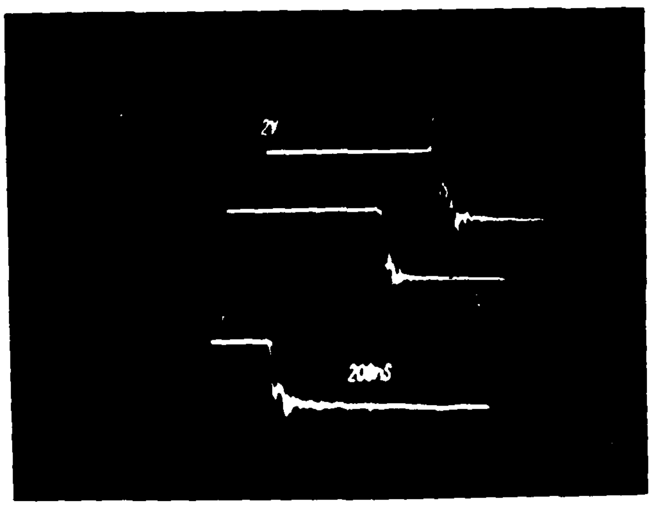

Figure 4. Anode One Voltage Variations Due to Changes in Trigger Timing.

Vertical - 2 kV/div - all traces
Horizontal - 200 ns/div - all traces

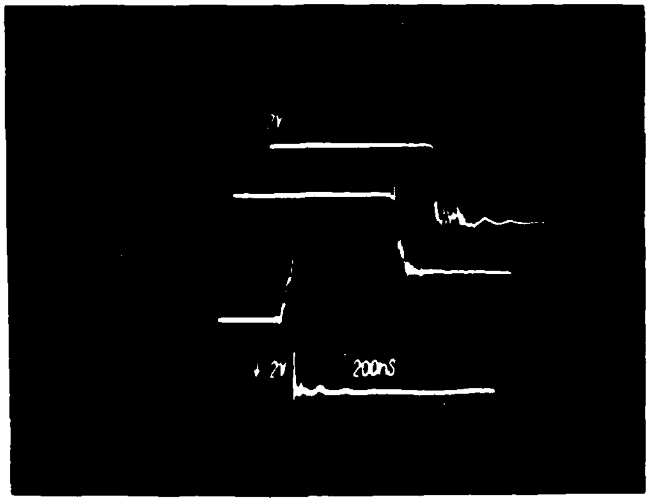

Figure 5. Anode Two Voltage Variations Due to Changes in Trigger Timing.

Vertical - 2 kV/div - all traces
Horizontal - 200 ns/div - all traces

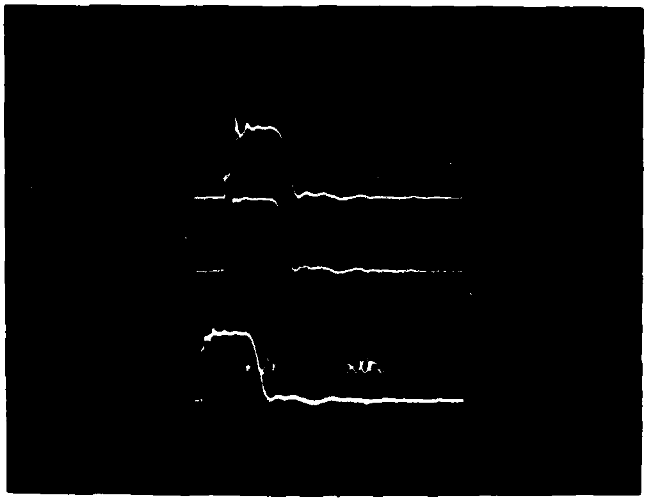

Figure 6. Load Voltage Variations Due to Changes in Trigger Timing.

Vertical - 2 kV/div - all traces
Horizontal - 500 ns/div - all traces

A spike always appears on the anode voltage of whichever thyratron is firing last. When the firings of the tubes are brought closer together in time, the anode spike decreases in magnitude and the output voltage waveshape improves. This seemed to indicate that both tubes should be fired at the same time. Although anode voltage spikes were eliminated by firing the thyratrons simultaneously, the resulting output waveform was not the optimum one obtainable. Best output shape occurred when tube one was triggered approximately 35-40 ns before tube two. It is probable the lead time in triggering tube one is required to charge the stray capacitances present in the second stage of the Marx.

Table I shows the relationship between the spike on tube two's anode voltage and the time difference between triggering tubes one and two.

Data in Table I shows the trigger timing between tube one and tube two must be small if the anode spike is to be held down and provides an excellent diagnostic tool for internal triggering. Table I is derived from information in Appendix B. Exact time differences in Table I should not be expected to hold for other Marx generators, due to differences in PFN's and construction, but the relationship should be similar and may be derived for another circuit.

Internal Triggering

After the trigger timing requirements and diagnostics were established, experimentation to trigger tube two from an event in stage one began. Many trigger circuits and locations are possible, but the circuit in Figure 7 offered an excellent chance for success. This

TABLE I

Trigger Diagnostics

Time Difference Between Tube One and Two Anode Voltage Falls	Tube Two's Anode Voltage Spike Amplitude
35 ns	400 v
40 ns	1000 v
50 ns	2000 v
60 ns	3000 v
70 ns	4000 v

trigger circuit was selected because it didn't add inductance to the discharge path of the erected Marx. Energy for the trigger circuit comes from the power supply and not from the erecting Marx. The trigger circuit is fully charged before erection of the Marx begins.

Circuit and Component Description. Main Marx circuitry is the same as described under Manual Triggering, with the internal trigger circuit being the only addition.

The trigger circuit consists of a 500 picofarad (pF), 30 kV capacitor (as determined in Appendix C) in series with the primary side of T_2, a 1:1 transformer. The capacitor is connected to the anode and the remaining primary lead of the transformer is connected to the cathode of tube one. The positive lead of the secondary is connected to tube two's grid and the negative lead is connected to the cathode of tube two. Figure 8 shows the two-stage Marx with the trigger circuit added.

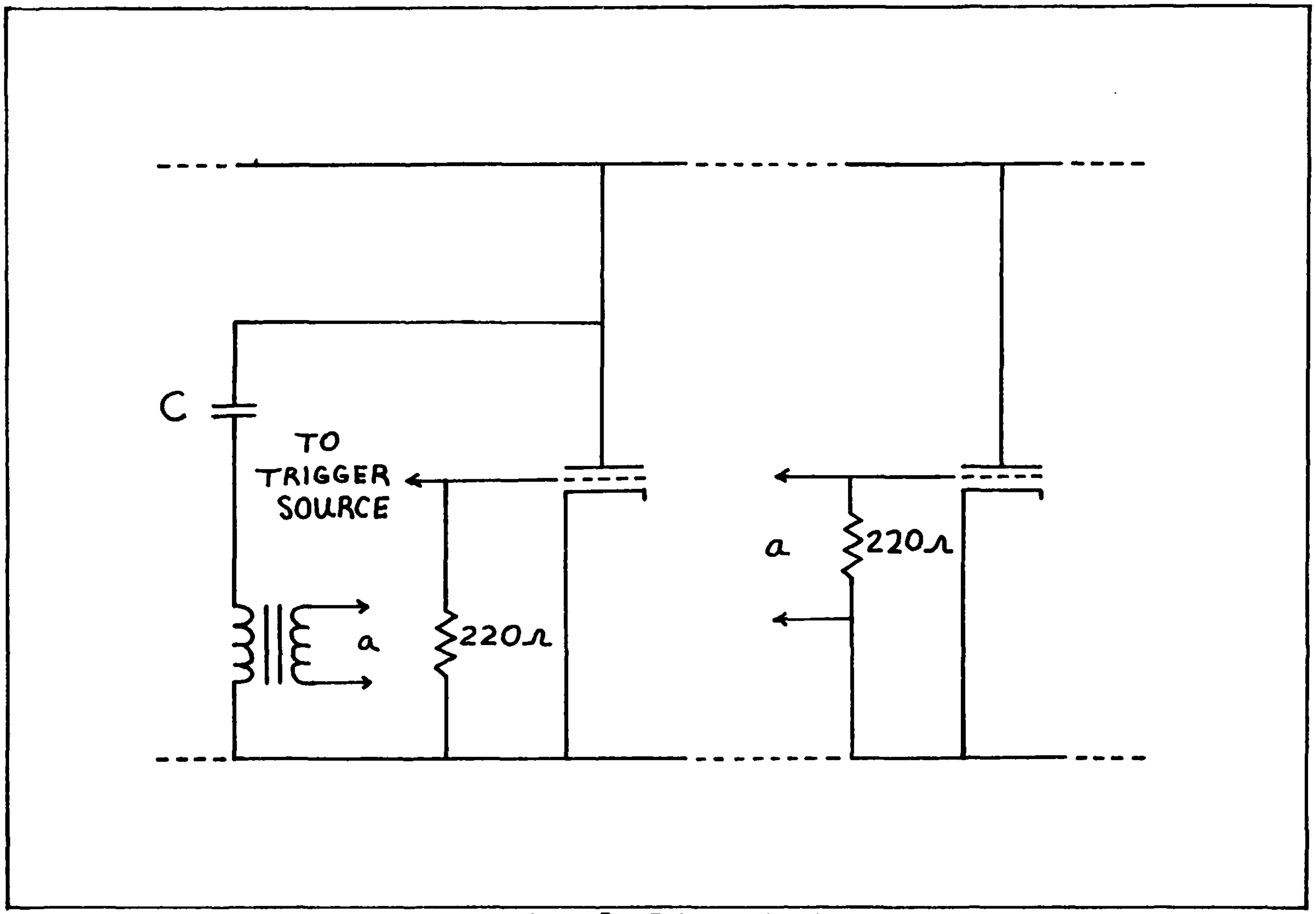

Figure 7. Trigger Circuit

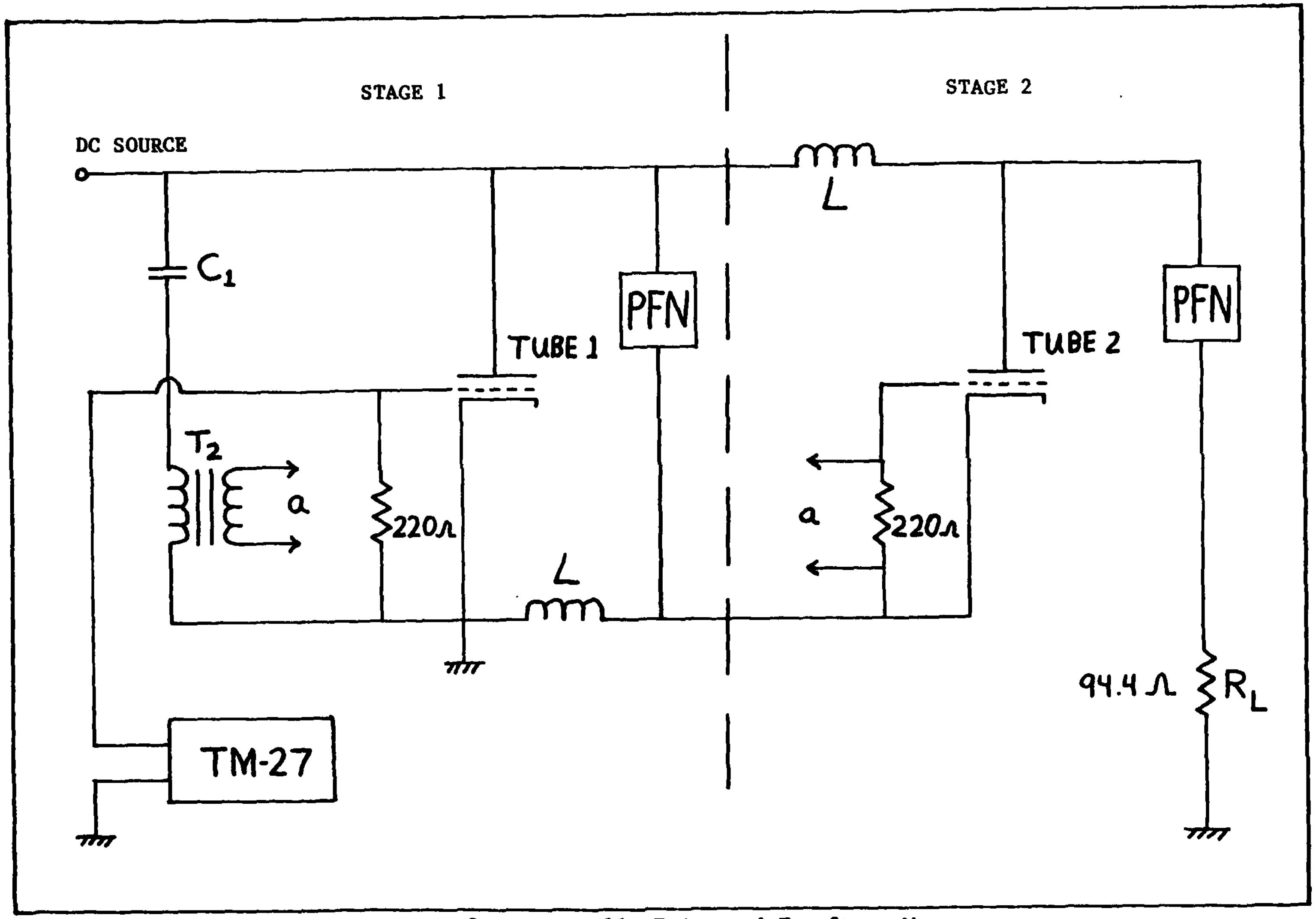

Figure 8. Internally Triggered Two-Stage Marx

Operating Conditions. Operating conditions were the same as given in Manual Triggering.

Sequence of Operation. The operating sequence occurs as follows:

1. Tube one is fired by the TM-27. When the anode-cathode space is capable of supporting a conductive plasma, C_1 rapidly discharges due to its low inductance mesh. The mesh containing the first PFN and tube one has a larger inductance and current out of the PFN should rise slower that the current in the mesh containing C_1. When C_1 discharges through the primary of T_2, a voltage is developed on the secondary of T_2.

2. Tube two is fired by the energy from the secondary of T_2, turning on its grid-cathode space which then ionizes its grid-anode space. The second PFN begins to discharge.

Results. Anode voltages of the internally triggered two-stage Marx are shown in Figure 9. The top trace is anode two voltage and the bottom trace is anode one voltage. The traces were separated vertically for clarity.

Anode two had a voltage spike of 3000 volts and there was a time difference of 65-70 ns between the two anode falls. An explanation of how the time difference was measured may be found in Appendix B. This time difference corresponds closely with the time difference for a 3000 volt anode spike in Table I.

Tube two was being fired far too late and several changes to the circuit were made in an attempt to fire tube two sooner. The attempted circuit changes are discussed in Appendix B. All attempts to decrease the time difference failed.

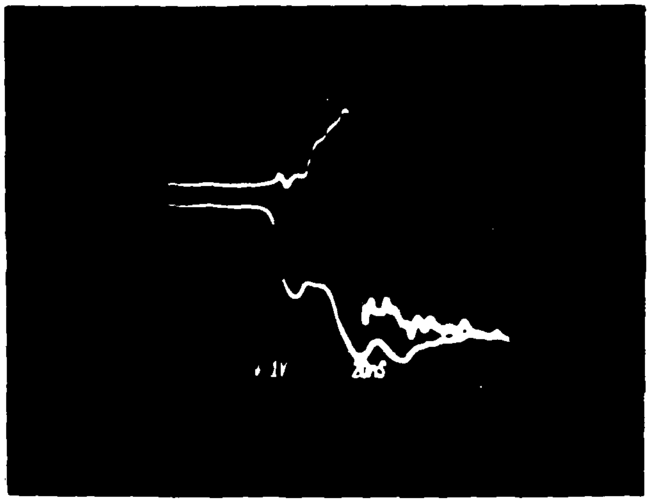

Figure 9. Anode Voltages of Internally Triggered Two-Stage Marx

Vertical - 1 kV/div - all traces
Horizontal - 20 ns/div - all traces
Top - Tube Two
Bottom - Tube One

The trigger circuit output was disconnected from the second stage and the Marx was turned on to verify the trigger circuit was firing tube two. Without the trigger circuit the second tube would still fire, but at a later time, due to capacitive division between the stray capacitance from anode to grid and grid to cathode. The Marx would erect in this manner, but the output pulse shape was poor and the anode voltage spike approached the charging voltage of 6 kV.

It was decided that triggering the N+1 stage from the Nth stage was not possible, but triggering the N+2 stage from the Nth stage had a high probability of success. This optimism was due to the fact that a 35–40 ns time difference between the anode falls gave a good output shape, when manually triggered, and internal triggering was giving a time difference of 65–70 ns between the anode falls.

III. Three-Stage Marx Generator

Introduction

Trigger timing results from experiments with the two-stage Marx generator demonstrated it would not be possible to trigger the N+1 stage from the Nth stage because the trigger circuit could not turn the next tube on soon enough. This forced development of a triggering scheme where energy in the Nth stage could be used to fire the N+2 stage of the Marx.

Manual triggering of all three stages was looked at to verify results from the two-stage Marx and then internal triggering of the third stage from the first, with the first and second stages triggered manually, was examined.

Manual Triggering

Trigger circuitry was set up so the three thyratrons could be fired in any order with any desired separation between the anode falls.

Circuit and Component Description. Circuit components are the same as the two-stage Marx, with one more stage added. Isolation was needed for the third stage trigger source and is provided by T_3, shown in Figure 10. T_3 is a 1:1 hand wound transformer using a ferromagnetic, tape wound, toroid wrapped with 10 turns (each side) of #14 teflon insulated wire. Triggering for the third stage was provided by a Cober 605P pulse generator and another carborundum resistor was added to the load for a total resistance of 140 ohms.

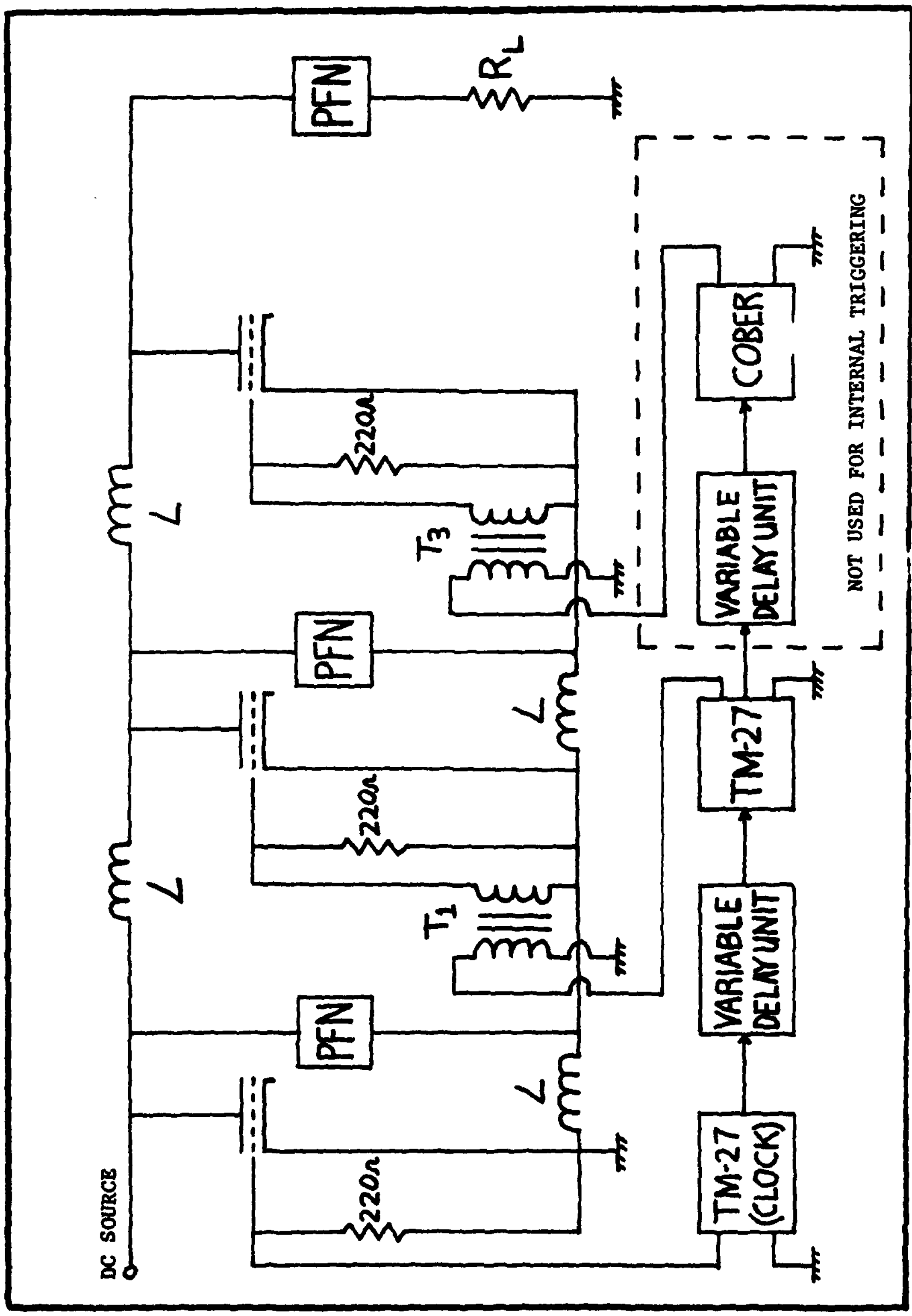

Figure 10. Three-Stage Manually Triggered Marx

Operating Conditions. Conditions of operation are the same as stated for the two-stage Marx.

Results. It was found that the tubes could be fired in any order and still give an acceptable output pulse shape, with proper timing of the triggering. Best results, however, were obtained with a 1, 2, 3 firing order, as expected.

Figure 11 shows the anode fall time differences between tubes one, two and three for the best output pulse shape obtained. Anode three voltage is the top trace with anode two voltage and anode one voltage being the middle and bottom traces respectively. The traces are separated vertically for clarity and jitter in the traces is due mainly to the trigger drivers.

A good load pulse shape was obtained with tube one firing 20-30 ns before tube two, with tube three firing anywhere between 0 and 25-30 ns after tube two. Timing requirements for the three-stage Marx have become a little tighter, especially between the second and third stages. It is felt the significant decrease in time difference between the last two stages is due to the stray capacitances being partially charged when tube one is fired.

Figure 12 shows the negative polarity load voltage and load current associated with the anode fall time differences shown in Figure 11. The top trace is voltage with the bottom trace being current. The traces are separated vertically for clarity.

Internal Triggering

The first and second stages were triggered manually using TM-27's, with the third stage being triggered from the first. This triggering

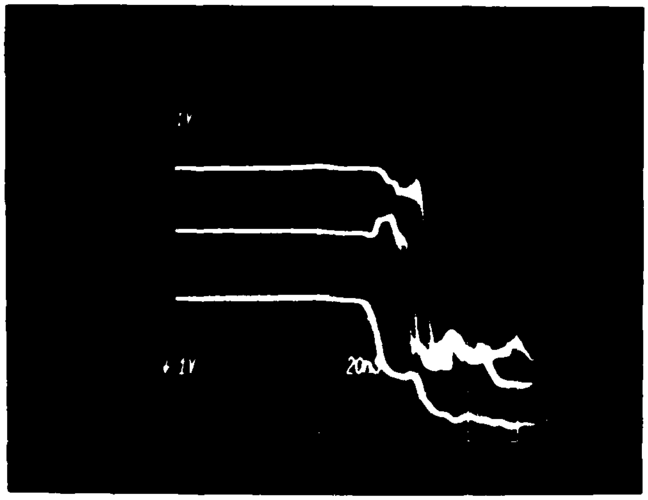

Figure 11. Anode Voltages for Three-Stage
Manually Triggered Marx

Vertical - 1 kV/div - all traces
Horizontal - 20 ns/div - all traces
Top to Bottom - Tubes 3, 2 and 1

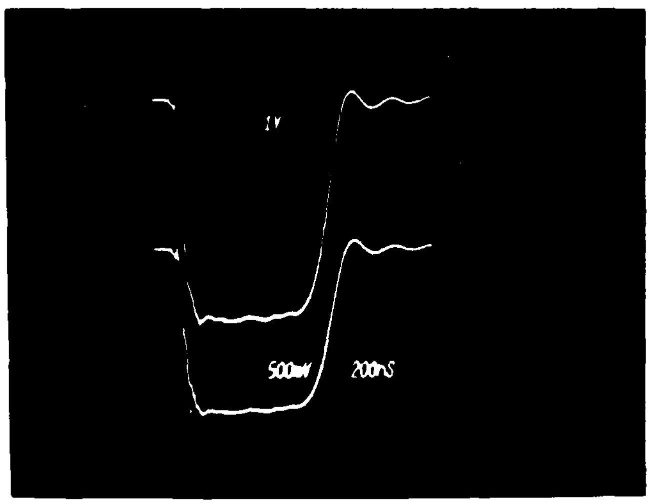

Figure 12. Output Voltage and Current for
Three-Stage Manually Triggered Marx

Vertical - Top-Load Voltage 1kV/div
- Bottom-Load Current 10A/div
Horizontal - Both Traces 200 ns/div

scheme only allows the first two stages to be adjusted independently.

Circuit and Component Description. Circuitry is the same as shown in Figure 10, except T_3 is no longer needed and the same internal trigger circuit used in the two-stage Marx is put across tube one. The output of the trigger circuit is now connected to the third stage tube.

Operating Conditions. Conditions of operation are the same as stated for the two-stage Marx.

Sequence of Operation. Sequence of operation is not given for the three-stage Marx, but is stated for the four-stage Marx in Chapter IV. The information in Chapter IV may be used to easily obtain a sequence of operation for the three-stage Marx.

Results. Since timing for the three-stage Marx was found to be highly variable, it was decided to look at all three anode voltage falls equally spaced. Success of this case would imply the method could be used for Marx generators having a larger number of stages.

Figure 13 shows the three anode voltage falls almost evenly spaced in time. The top trace is tube three anode voltage fall with the middle and bottom traces being the anode voltage for tube two and tube one respectively. This time spacing did not provide the optimum output pulse, but still gave a very nice current load pulse shape, as shown in Figure 14. Traces in Figure 13 are separated vertically for clarity.

Note, from Figure 13, that tube three's anode voltage fell about 70 ns after the anode fall of tube one and the anode voltage spike for a time difference of 30-35 ns, between adjacent anode falls, corresponds very well with data in Table I.

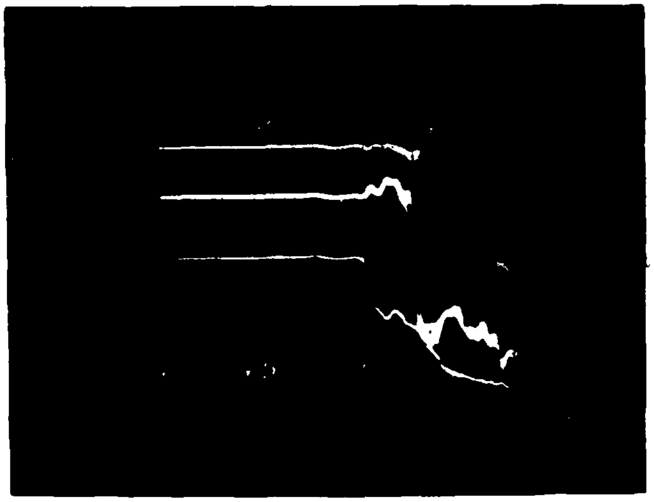

Figure 13. Anode Voltages of Internally Triggered Three-Stage Marx

Vertical - 1 kV/div - all traces
Horizontal - 20 ns/div - all traces
Top to Bottom - Tubes 3, 2, and 1

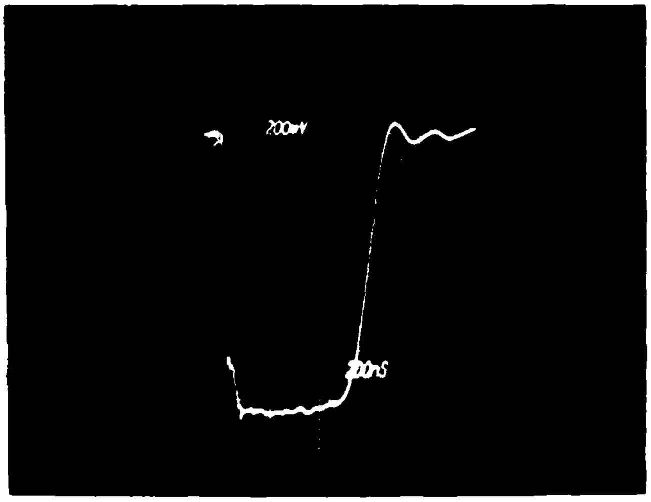

Figure 14. Load Current for Internally Triggered Three-Stage Marx

Vertical - 6A/div
Horizontal - 200 ns/div

IV. Four-Stage Marx Generator

Introduction

This chapter contains the test results for a four-stage Marx generator using the internal triggering scheme presented in Chapter II and III. Variations in the basic trigger circuit design and their effects on operation are found in Appendix C. Also included here are the sequence of operation for this circuit, a concept of operation check and demonstrated circuit capabilities.

Circuit and Component Description

The circuit is the same as the three-stage Marx, but with one more internally triggered stage added. The four-stage circuit is shown in Figure 15. The transformers in the internal trigger circuits, T_4 and T_5, are constructed the same as T_2 in the two-stage circuit except they are wound as step-up transformers with a 1:2 turns ratio. Another carborundum resistor was added to the load making the total load resistance 188 ohms.

Operating Conditions

Operating conditions were the same as the three-stage Marx. Heater voltages were 6.3 volts RMS. The peak anode voltage, e_{py}, was 6 kV. The repetition rate was 100 Hz. The firing of the second thyratron was delayed 30 ns from that of the first tube due to results of the two and three-stage Marx experiments.

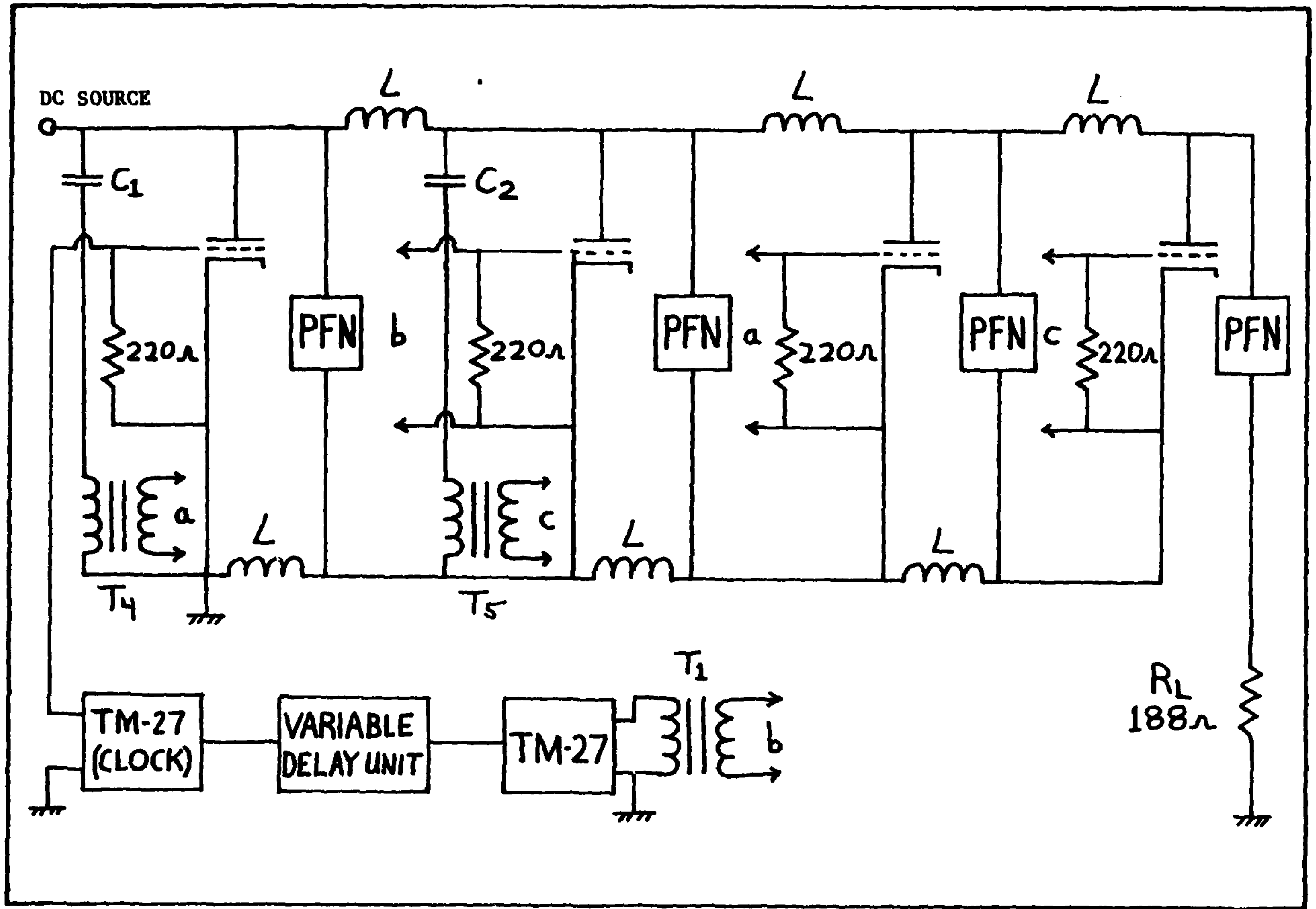

Figure 15. Four-Stage Internally Triggered Marx Generator

Sequence of Operation

The objective of the circuit in Figure 15 was to fire the tubes in sequence (1,2,3,4) with the timing arranged so that the grid-cathode space of tubes two, three and four would be ionized just before the leading edge of the PFN pulse arrived at the tube. If these conditions were met, the thyratrons would not be fired by overvolting, thus increasing the life of the tube and yielding a well formed output pulse.

The erection sequence is as follows:

1. Tube one is fired by the trigger source. As the anode-cathode space conducts, C_1 immediately begins discharging due to its low inductance circuit mesh as seen in Figure 16. The discharge of C_1 thru the primary of T_4 develops a voltage on the secondary of T_4. Current flow out of the PFN rises more slowly because of the section of inductance connected to the anode of the thyratron.

2. Tube two is fired after tube one, with any desired delay, by the external trigger circuitry. C_2 and the second PFN discharge in the manner described above in step 1. The discharge of C_2 develops a voltage on the secondary of T_5.

3. Energy from the secondary of T_4 causes the anode-cathode space of tube three to ionize. The third PFN begins to discharge.

4. Energy from the secondary of T_5 ionizes tube four. The fourth PFN begins to discharge.

5. The resultant output pulse appears across the load, delivering all stored energy in the PFN's to the load.

6. The voltage across the thyratrons drops to zero or becomes slightly negative.

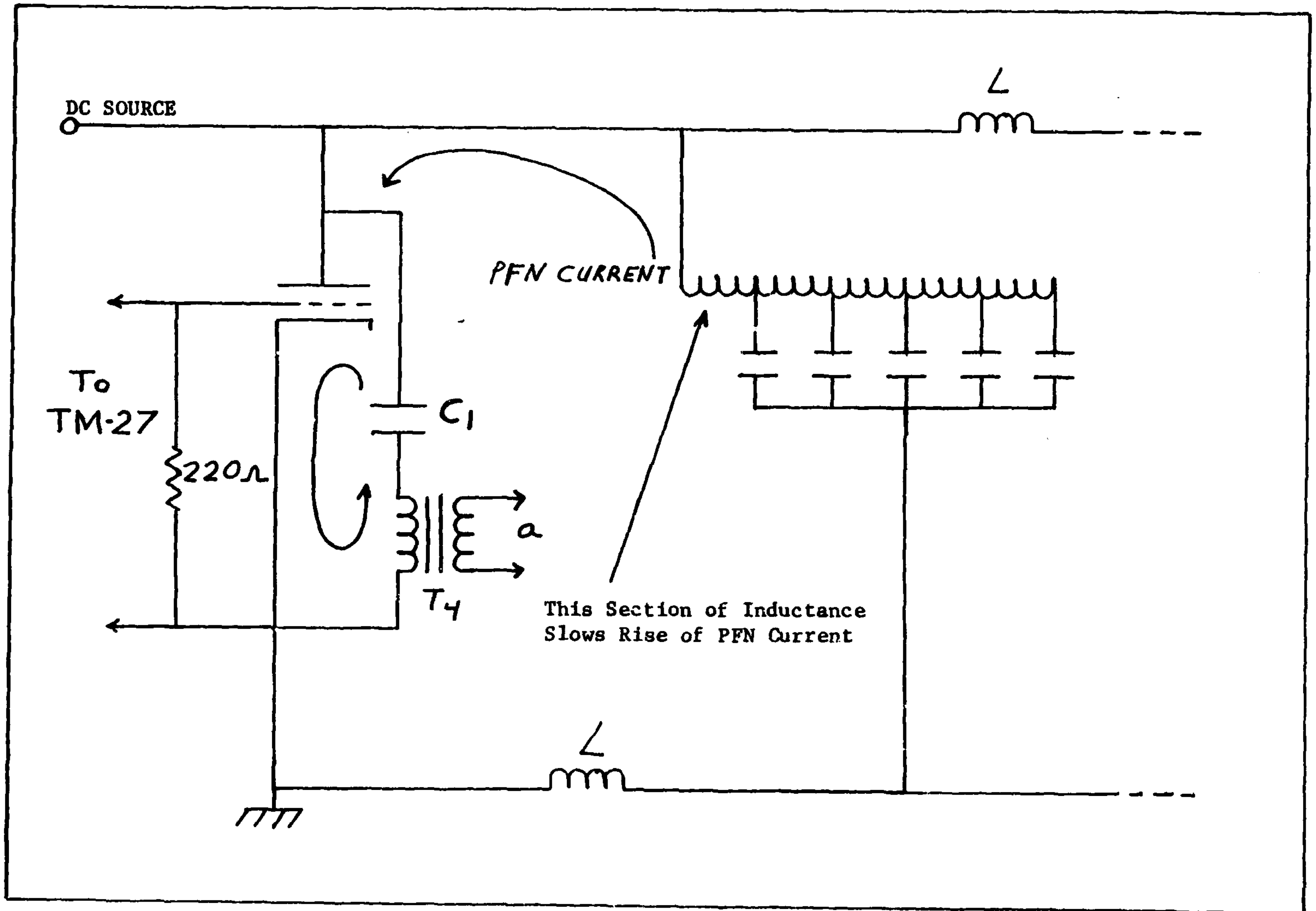

Figure 16. Anticipated Initial Current Flow in Stage One

7. The thyratrons deionize, recovering their voltage holdoff capability.

8. C_1, C_2 and the PFN's begin to recharge from the power supply.

Results

The anode voltages for all four thyratrons are shown in Figure 17. The time between each anode fall is 30-35 ns. While small anode spikes are present on the third and fourth thyratrons, they do not cause firing due to overvolting. The traces are separated vertically for clarity.

The load voltage output waveshape is presented in Figure 18. The waveform has a risetime (10-90%) of 100 ns and a small amount of ripple. Each pulse delivers about 0.78 joule to the load (12 kV x 65 A x 1 μs = 0.78 joule).

An interesting and significant result is the risetime of the load pulse. The load pulse has a 10-90% risetime of 100 ns with a time to major break of 70 ns. The PFN's times were 175 ns and 175 ns, which are considerably slower. This could possibly be caused by a sharpening effect from each stage. More work is needed in this area to determine the exact cause of output pulse sharpening.

Concept of Operation Check

To insure that the internal trigger circuits were actually responsible for firing the third and fourth thyratrons, several checks were made. First, only the primary sides of T_4 and T_5 were disconnected. Then only the secondary sides of T_4 and T_5 were disconnected. Finally, the internal trigger circuits were completely removed from the Marx generator circuit. The Marx did not operate in an acceptable manner for any of these conditions.

Figure 17. Anode Voltages for
Four-Stage Marx, 100 Hz, e_{py} = 6 kV

Vertical - 1 kV/div - all traces
Horizontal - 10 ns/div - all traces
Top to Bottom - Tubes 4, 3, 2 and 1

Figure 18. Load Voltage for
Four-Stage Marx

Vertical - 1 k/div
Horizontal - 200 ns/div

In all three cases, the results were the same. Excessive anode voltage spikes characteristic of overvolting appeared on tubes three and four. The output pulse waveshape had a ragged leading edge and a large amount of ripple on the top of the pulse. Only minimal control of the anode voltage spikes and the output waveshape could be achieved by varying the time delay between tubes one and two. No timing setting could reduce the anode voltage spikes to an acceptable level or return the output pulse waveshape to that shown in Figure 18.

These results show that proper firing of tubes three and four is due to the internal trigger circuit and not capacitive division or inductive coupling effects. This fact, coupled with the expected slower rise in PFN current in relation to trigger current, illustrated in Figure 19, indicates that the assumed sequence of operation is correct. The top trace in Figure 19 shows the rise in current out of the first stage trigger capacitor while the bottom trace shows the current rise out of the first stage PFN. The traces are separated vertically for clarity.

Circuit Capabilities

Once the baseline data was collected, the peak anode voltage, e_{py}, and repetition rates were varied to the limits of the power supply and circuit insulation as seen in Table II.

The output waveshapes remained constant with variations in repetition rate and charging voltage. The only effect noted was the introduction of a small amount of noise as the load voltage rose above 22 kV, which is probably caused by inadequate shielding of the oscilloscope and leads.

TABLE II

Circuit Capabilities

Frequency	Load Voltage	Limit
100 Hz	26 kV	Insulation of T_4
1000 Hz	12.5 kV	Power Supply
2000 Hz	6 kV	Power Supply

Figure 19. Current Delay
Vertical - 1 kV/div - both traces
Horizontal - 5 ns/div - both traces
Top - Trigger Current, Bottom - PFN Current

The most important and encouraging effect of raising the charging voltage can be observed on the anode voltage of the fourth tub. Figure 20 displays tube four's anode voltage for two cases with the heaters at 6.3 volts RMS and a repetition rate of 100 Hz. The lower

Figure 20. Effect of Increasing e_{py} on Tube Four's Anode Voltage

Vertical - 2 kV/div - both traces
Horizontal - 100 ns/div - both traces

trace represents an e_{py} of 6 kV. The upper trace was taken with e_{py} of 12 kV. Notice that the anode voltage spike does not increase proportional to the increasing value of e_{py}. This means that e_{py} can be raised to nearly the voltage holdoff limit of the tube without firing due to an overvolting caused by the spike.

There are two possible causes for this effect:

1. The increasing energy stored in the trigger circuit capacitor. This energy increases by the square of e_{py} and could cause the tube to turn on faster.

2. The increasing anode voltage brings the tube nearer to its self breakdown voltage. The nearer the thyratron is to its breakdown voltage, the easier it is for the same grid signal to turn on the tube.

Trigger Circuit Expansion

To determine if the internal trigger circuit could be used in a Marx that had more than four stages, internal trigger circuits with dummy loads were attached to tubes three and four as shown in Figure 21. The operating conditions were the same as the basic four-stage Marx experiment.

The output waveshape and tube four's anode voltage were compared with and without the dummy-loaded trigger circuits in stages three and four. There were no observable differences between the sets of waveforms. This indicates that a stage fired by an internal trigger circuit can fire another stage without adversely affecting Marx operation.

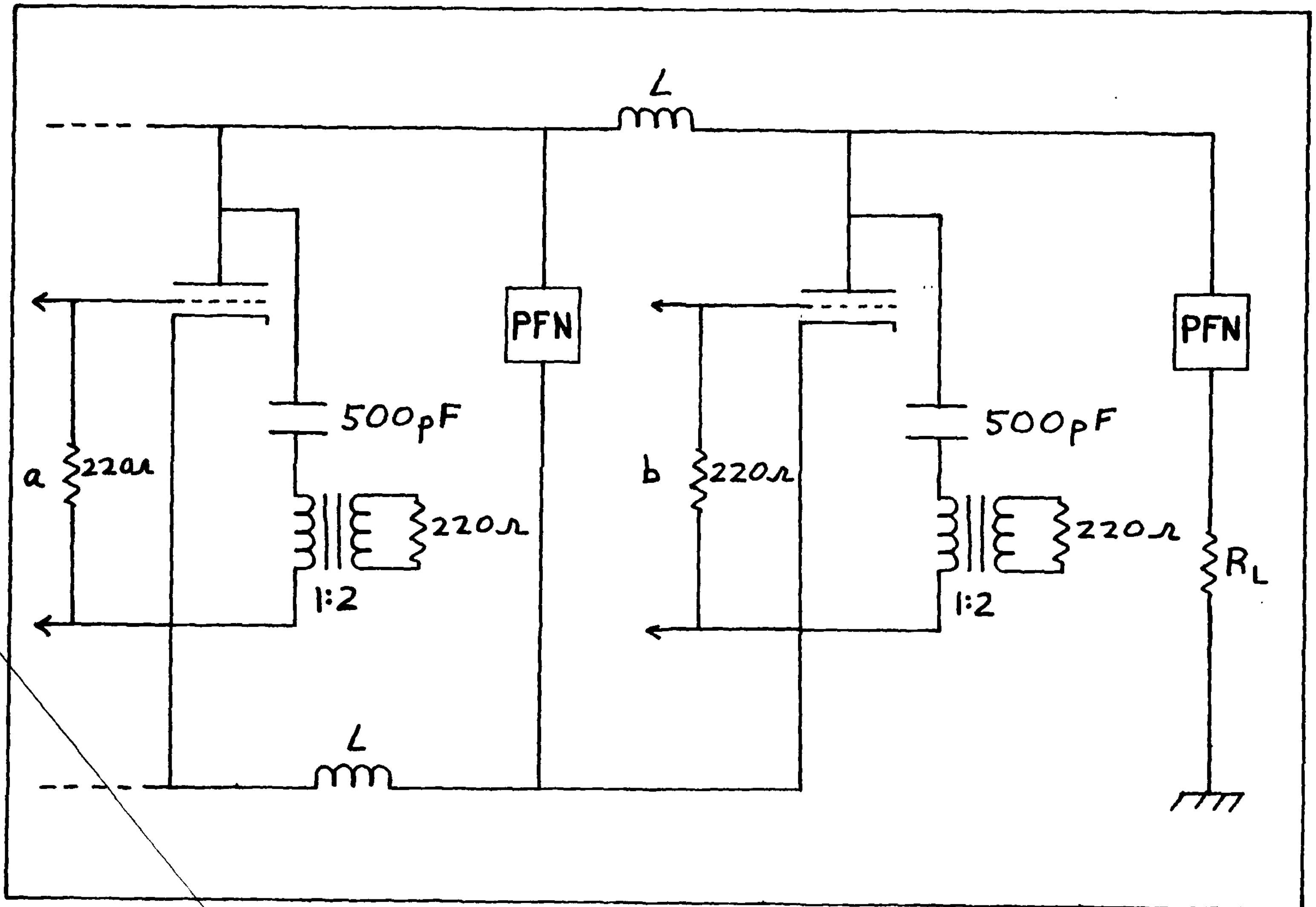

Figure 21. Trigger Circuit Expansion Experiment

V. Conclusions and Recommendations

It is possible to use an internal triggering scheme to fire hydrogen thyratrons employed as switches in a Marx generator and achieve a well-formed output pulse.

Recommendations

Based on observations made during the investigation, the following recommendations are proposed for further study:

1. Although a workable triggering circuit was proven, more experiments should be conducted to find a faster method of triggering.
2. Investigate what effect the number of stages in the Marx has on the risetime of the output pulse.
3. Additional experiments are required to completely verify the sequence of operation assumed in Chapter IV.
4. Replace the PFN's with lengths of coaxial cable to examine Marx operation with a fast risetime pulse. It is possible a fast pulse may require the time difference between anode falls to be very small in order to prevent excessive anode spikes.
5. A five or six-stage Marx should be constructed to prove that a stage fired by the internal trigger circuit can actually fire another stage as indicated by the experiment with trigger circuits attached to tubes three and four as described in Chapter IV.

6. Construct and operate the positive output Marx proposed by Ewanizky (Ref 2:193) to determine if this circuit will prevent elevated voltages from appearing on upper stage thyratrons.

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Appendix A

8613/HY1A Thyratron Experiments

This appendix presents the manufacturer's specifications, breakdown voltage experiments, tube turn-on experiments, and the procedure that determined the capacitance required for the internal trigger circuit.

Manufacturer's Specifications

Peak Output Power (Po)	5 Megawatts
Peak Forward Anode Voltage (e_{py})	20 Kilovolts
Peak Anode Current (ib)	500 Amps
DC Average Current (Ib) (= Duty Cycle x ib)	.5 Amps DC
Cathode Heater Voltage (Ef)	5.8-6.8 Volts AC
Cathode Heater Current (If)	5.5-8.5 Amps AC Ef = 6.3 Volts AC
Peak Forward Grid Voltage (e_{gy})	150 Volts Minimum
Impedance of Grid Circuit (Zg)	1500 Ohms Maximum

Breakdown Voltage Experiments

Thyratron static breakdown voltage tests were conducted to determine individual tube characteristics with the goal of normalizing all the tubes in a Marx generator to the same percentage of breakdown voltage by adjusting individual heater voltages.

The procedure for the breakdown tests follows:

1. A 47 ohm resistor was connected from the grid to the cathode.

2. The tube was allowed one half hour to warm up to the initial heater voltage setting.

3. The voltage across the thyratron was increased until the anode-cathode space ionized and then the voltage was removed.

4. The heater voltage was changed and allowed to stabilize for five minutes.

Results of these tests are presented in Table A-I and Figure A-1. Breakdown voltages were erratic and the ones given are the ones that occurred most frequently. Experiments with the two and three-stage Marx showed it was not necessary to adjust the individual heater voltages.

Tube Turn-On Experiments

Tube turn-on tests were conducted to find the grid pulse amplitude and width necessary to fire the thyratron at a particular anode voltage and heater voltage.

The procedure for the test follows:

1. The desired anode voltage and heater voltage were set.

2. The amplitude of the grid pulse was set.

3. Pulse width was increased until the tube began to fire, then reduced until the tube stopped firing to find the minimum pulse width required for that amplitude.

4. The grid pulse amplitude was changed and the test repeated.

Results of these experiments are presented in Tables A-II and A-III. Figure A-2 is a representative graph of the data in the tables.

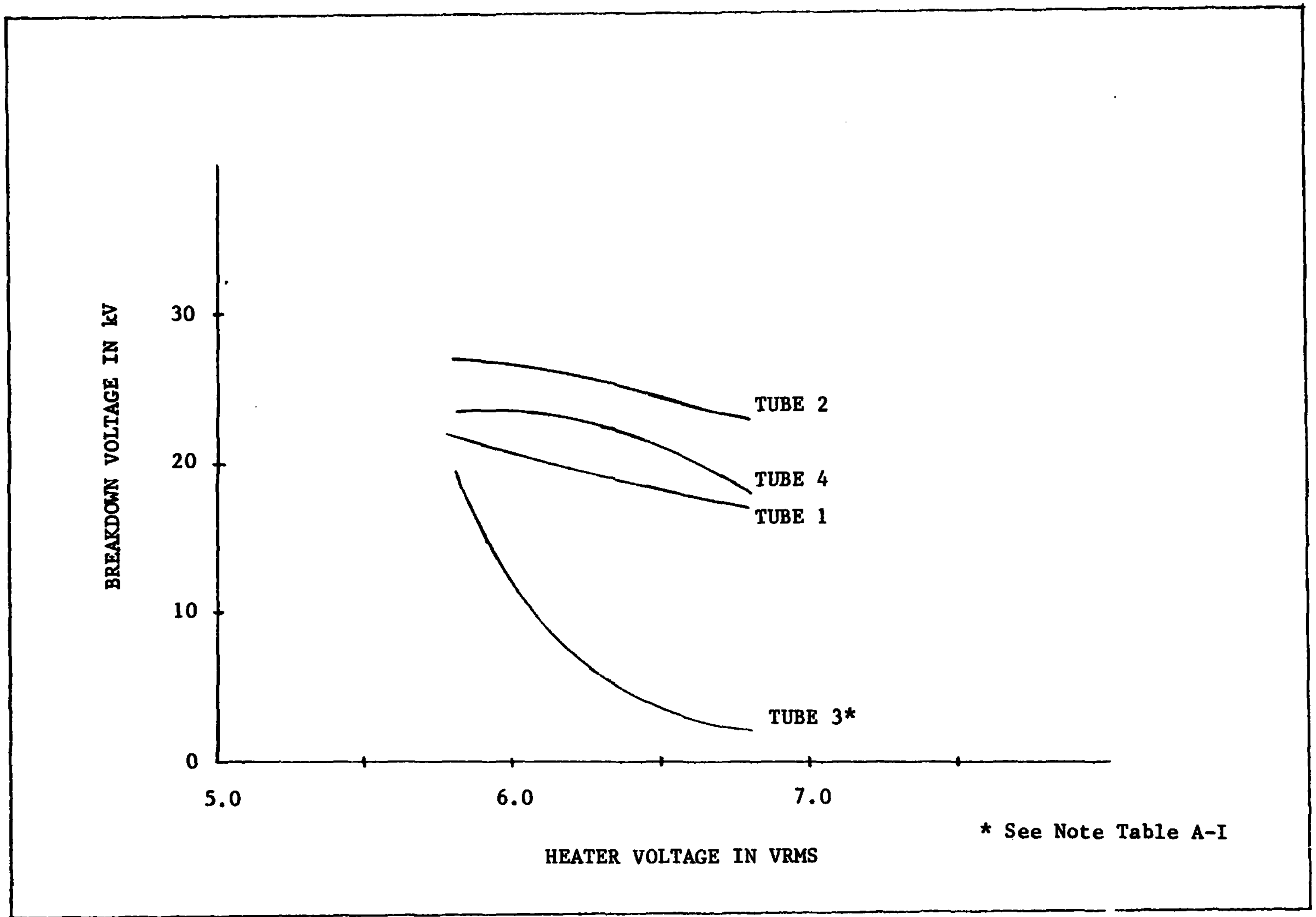

Figure A-1. Breakdown Voltage Vs. Heater Voltage

TABLE A-I

Breakdown Voltage Test Results

Heater Voltage (VRMS)	Breakdown Voltage (kV)			
	Tube 1	Tube 2	Tube 3*	Tube 4
5.8	23.5	27	19.5	21.5
6.3	22.5	25.5	5.5	19
6.8	17.5	23	2	18

* This tube burned out during turn-on testing and was replaced. Breakdown voltage tests were not conducted for the new tube.

TABLE A-II

Tube Turn-On Test Results

Grid Pulse Amplitude in Volts	Grid Pulse Duration in μs			
	Anode Voltage = 6 kV		Anode Voltage = 9kv	
	Tube 3*	Tube 4	Tube 3*	Tube 4
25	1.92	1.92	1.94	1.98
30	1.4	1.06	.89	1.08
40	.63	.63	.59	.6
50	.445	.435	.435	.425
60	.36	.355	.35	.35
80	.26	.25	.25	.24
100	.23	.23	.225	.225
120	.215	.218	.216	.212
140	.212	.208	.208	.2

Heater Voltage = 5.8 VRMS
Repitition Rate = 100 Hz
Grid Leak Resistor = 47 ohm

* This is not the same tube on which the breakdown voltage tests were conducted.

TABLE A-III

Tube Turn-On Test Results

Grid Pulse Amplitude in Volts	Grid Pulse Duration in μs			
	Anode Voltage = 6 kV		Anode Voltage = 9 kV	
	Tube 3*	Tube 4	Tube 3*	Tube 4
25	1.6	1.44	1.32	RESULTS WERE THE SAME AS 6kV TEST
30	.9	.96	.79	
40	.525	.55	.495	
50	.39	.4	.37	
60	.31	.29	.27	
80	.215	.225	.222	
100	.206	.204	.22	
120	.192	.19	.192	
140	.178	.18	.178	

Heater Voltage = 6.3 VRMS
Repitition Rate = 100 Hz
Grid Leak Resistor = 47 ohm

* This is not the same tube on which the breakdown voltage tests were conducted.

If tests of this nature are performed in the future, grid current should be measured instead of grid voltage amplitude. Then the amount of charge necessary to fire the tube could be easily calculated.

Selection of Internal Trigger Capacitance

The value of the capacitor in the internal trigger circuit presented in Chapter II was determined by the amount of charge necessary to turn on the tube. The charge required was found by using oscilloscope pictures of the grid current. Area underneath the trace

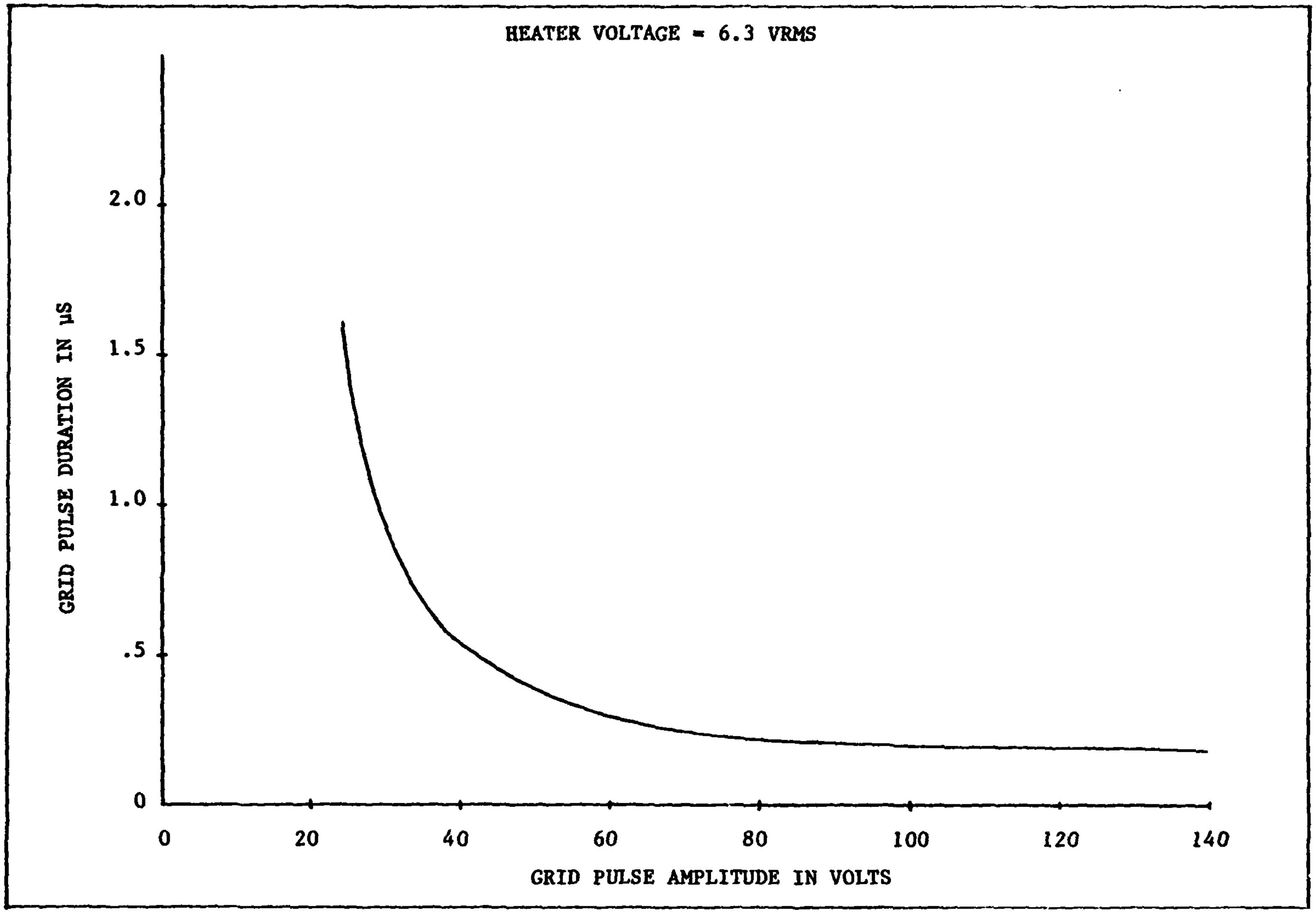

Figure A-2. Grid Pulse Duration Vs. Amplitude Tube 3 represented the charge transferred to the grid (charge = $\int i\,dt$). Using the relation Q=CV, the capacitance required to store that amount of charge for a given voltage could be found.

For an e_{py} of 6 kV, heater voltage of 6.3 VRMS and repetition rate of 100 Hz, a tube would turn on with a charge of $.225 \times 10^{-6}$ coulomb applied by the trigger source. At 6 kV, this value of charge requires a 37.5 pF capacitor.

To insure that a thyratron would always be fired from the internal trigger circuit, the capacitor's value was multiplied by a factor of 10. The nearest size capacitor available was the 500 pF employed in the experiments.

Appendix B

Two-Stage Marx Trigger Circuit and Modifications Attempted

This appendix looks at the effects of different component values in the trigger circuit, two additional circuits investigated, use of grid leak resistors, a brief look at magnetic delay and the pictures for reconstruction of Table I in Chapter II.

Trigger Circuit Component Modification

Different trigger circuit component values were used to determine the effect on triggering speed. The criterion for improvement was a time decrease between the fall of anode one and two voltages. Different sizes of capacitors ranging from 250 pf to 1000 pf were tried and the circuit was insensitive to the changes. Several transformer toroids were used to determine if a change in size or ferromagnetic material would decrease the time difference. The circuit was insensitive to these changes, too. Transformer turns ratios were not investigated but were examined with the four-stage Marx where it was found a 1:2 step up gave the best results.

Other Trigger Circuits

One additional trigger circuit and a combination of it with the original circuit were tried. Figure B-1 shows the additional circuit tried which should make the thyratron trigger itself thru capacitive division.

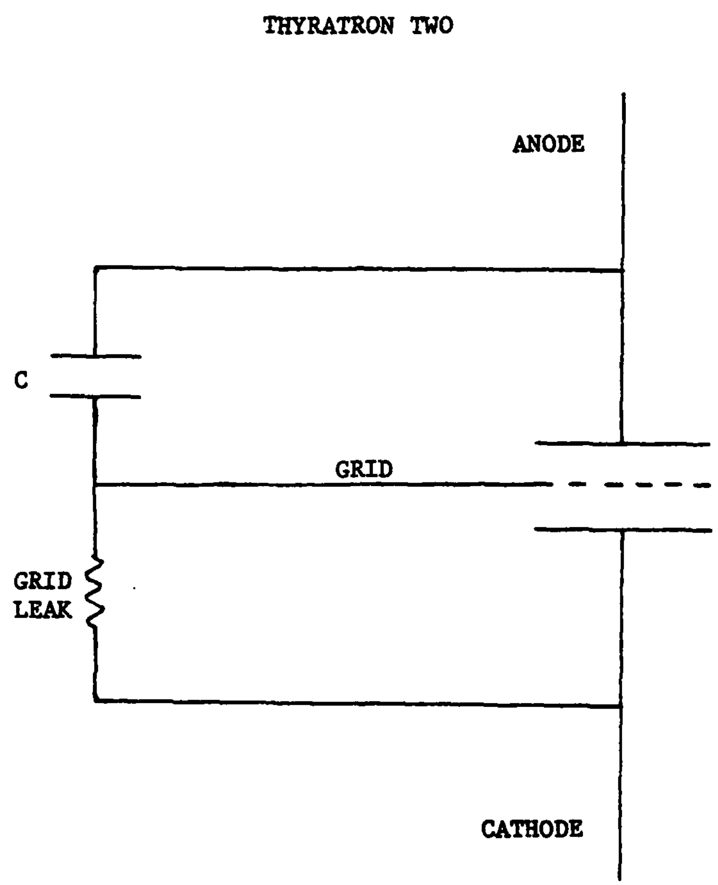

Figure B-1. Capacitive Division Trigger Circuit

Thyratrons have stray capacitances from anode to grid and grid to cathode that are relatively small. Putting a large capacitor from anode to grid will cause the anode to cathode voltage to be divided so the largest share is from grid to cathode. It was hoped the larger grid to cathode voltage would cause conduction to begin before the thyratron was overvolted. Anode voltage spike size decreased some and the time between anode falls remained the same. Different capacitance values, ranging from 500 pf to 1500 pf, were tried to reduce the voltage spike, but the spike remained constant.

Combining the original trigger circuit with the capacitive circuit was tried and the circuit was insensitive to this change. The circuit was the same as shown in Figure B-1 with a trigger input from tube one across the grid leak terminals. The trigger circuit used in Chapter IV gave the best results obtainable.

Grid Leak Resistors in Triggering

Grid leak resistors provide a shunt path for the trigger current, tie the grid to the cathode (shown in Figure B-2) and will effect the turn-on time of the thyratron. Tying the grid to the cathode loads down the grid to cathode capacitance and inhibits the voltage build up on the grid due to capacitive division. This was required at higher voltages to make the thyratrons operate reliably. Small impedance grid leaks rob the grid of trigger current and result in a slower, gentler turn on of the tube. Larger impedance grid leaks don't shunt as much of the trigger current and allow a faster tube turn on. Fine tuning of the turn on time may be accomplished by varying the size of the grid leak. Grid levels of 220 ohms were used in our work because it was

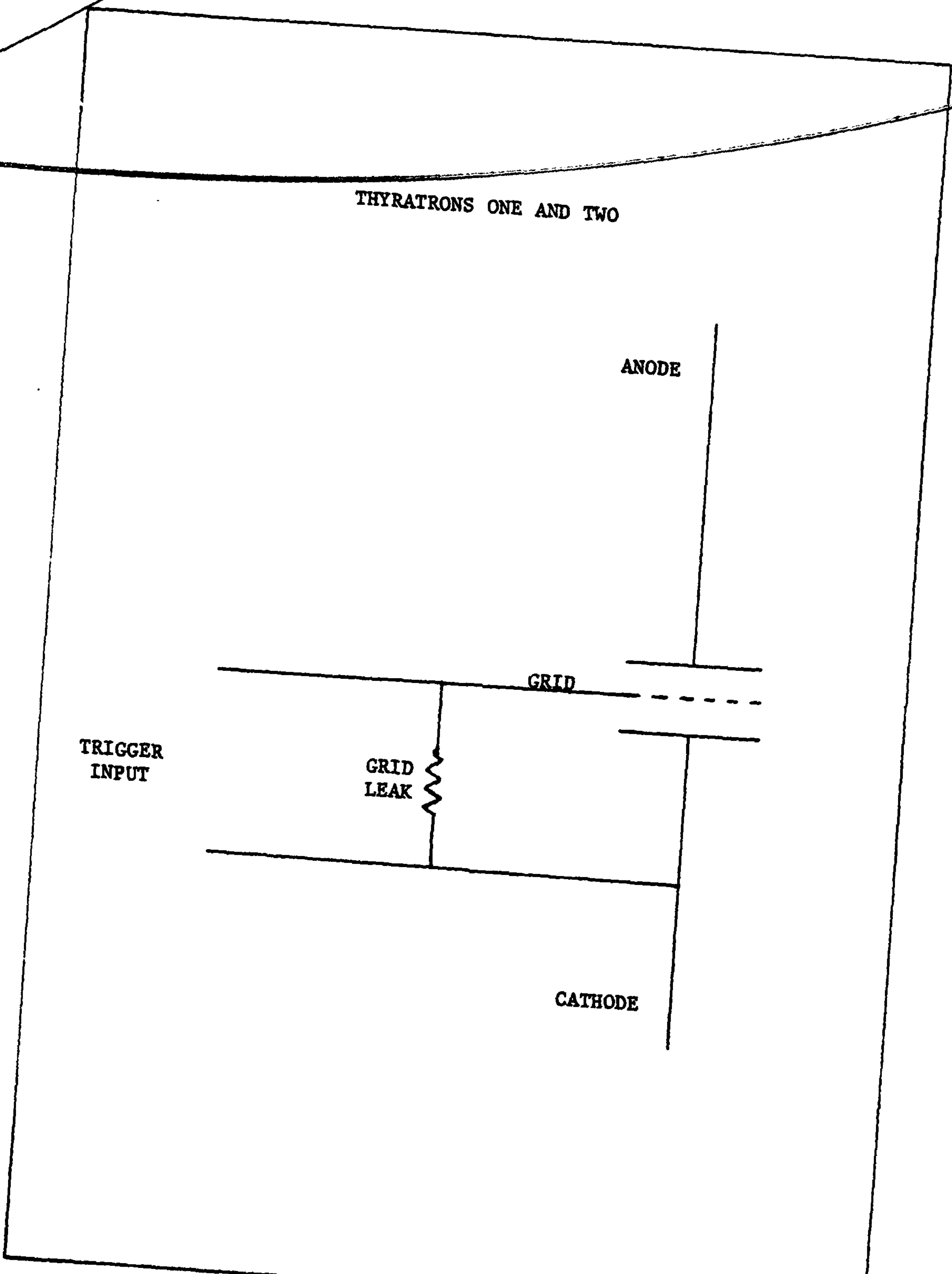

Figure B-2. Grid Leak Resistor Placement found this value kept the grid close enough to the cathode and didn't load the trigger signal.

Magnetic Delay

Ferromagnetic material was inserted in the anode lead of the first tube as shown in Figure B-3. The purpose was to delay the current thru the anode lead, giving the thyratron more time to reach a conductive state (Ref 3). Risetime of the PFN's was too slow for the amount of ferromagnetic material available. Magnetic delay may still prove valuable if faster PFN's are used.

Table I Reconstruction

Data for Table I in Chapter II were obtained from Figures B-4 thru B-8. The top trace in all five figures in the voltage on anode two with the bottom traces being the voltage on anode one. Trigger timing was adjusted to obtain a given anode voltage spike on tube two and then the time difference between the fall of anode one and anode two could be read off the picture.

Since both anodes did not fall in the same manner a definition was needed to measure the time difference. The measuring point for the first anode was taken in the middle of the steepest fall. The gradual slope was not used. Tube two was measured half way between the bottom of the steepest slope and the point where the spike starts to fall. The time difference between these two measuring points is used in Table I. Figure B-5 thru B-8 were separated vertically for clarity.

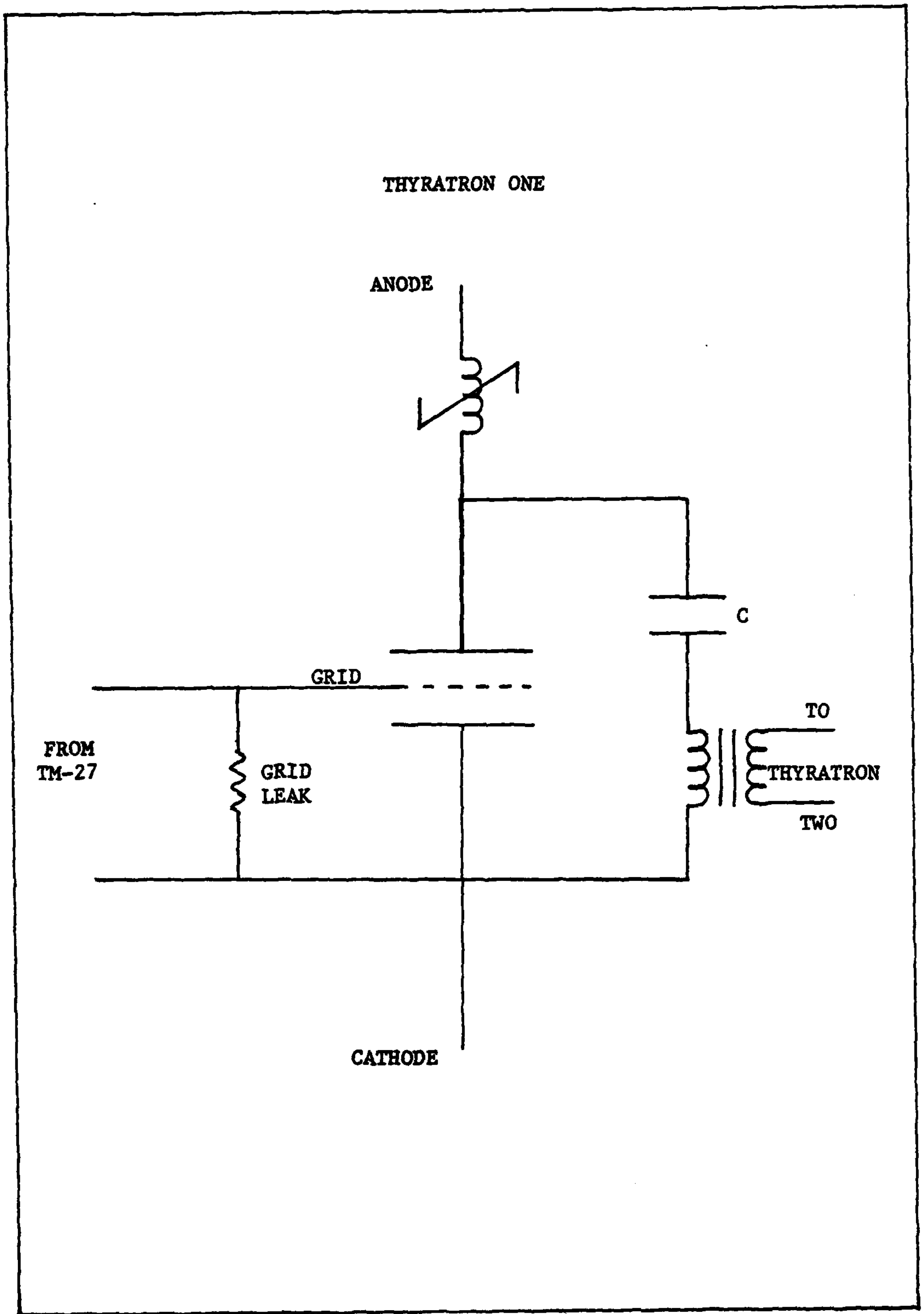

Figure B-3. Placement of Ferromagnetic Material

Figure B-4. Two-Stage Diagnostics
400 Volt Anode Spike

Vertical - 500 V/div - all traces
Horizontal - 20 ns/div - all traces

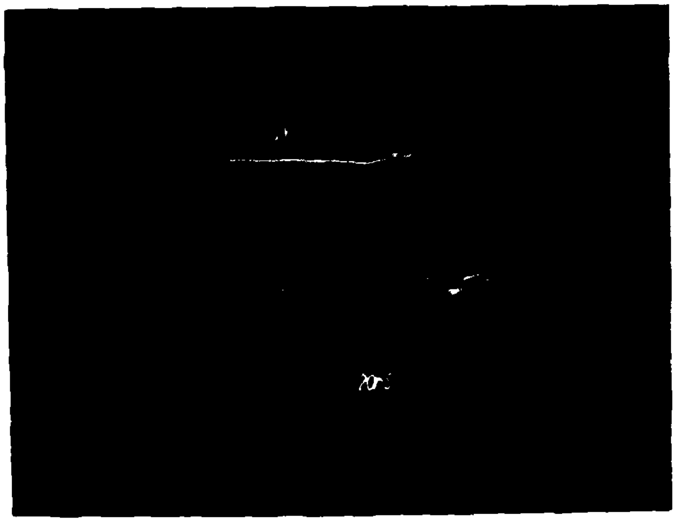

Figure B-5. Two-Stage Diagnostics
1 kV Anode Spike

Vertical - 1 kV/div - all traces
Horizontal - 20 ns/div - all traces

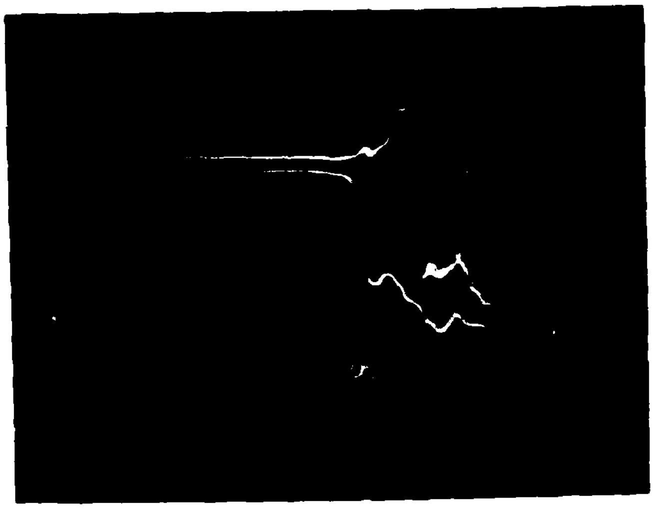

Figure B-6. Two-Stage Diagnostics
2 kV Anode Spike

Vertical - 1 kV/div - all traces
Horizontal - 20 ns/div - all traces

Figure B-7. Two-Stage Diagnostics
3 kV Anode Spike

Vertical - 1 kV/div - all traces
Horizontal - 20 ns/div - all traces

Figure B-8. Two-Stage Diagnostics
4 kV Anode Spike

Vertical - 1 kV/div - all traces
Horizontal - 20 ns/div - all traces

Appendix C

Variations in Trigger Circuit of Four-Stage Marx

This appendix presents the results obtained by varying the component values of the internal trigger circuits used in the four-stage Marx generator. Changes to component values refer to the same component in both triggers being altered at the same time. For these tests, the heater voltage was 6.3 VRMS, the repetition rate was 100 Hz, e_{py} was 6 kV, and the time between tubes one and two firings was 30 ns.

The original internal trigger circuit is shown in Figure C-1. The transformer consisted of a circular steel tape core of dimensions 2 3/8" OD, a 1 1/2" ID and 7/16" D with 10 turns of #14 teflon insulated wire on each winding.

Variations in Capacitance

With a capacitance of 500 pF the time difference between the firing of the Nth stage and the N+2 stage was 70 ns. The trigger capacitance was varied to determine its effect on this time delay. Table C-I presents the values used and the effects observed.

Although the Marx would run with capacitances less than 500 pF in the trigger circuit, it would not operate properly without first being exercised using the 500 pF capacitance. Attempting to begin operation with any value less than 500 pF resulted in arcing inside the tubes and an unacceptable output pulse shape. A longer warm-up period for the thyratrons before attempting operation did not remedy this condition.

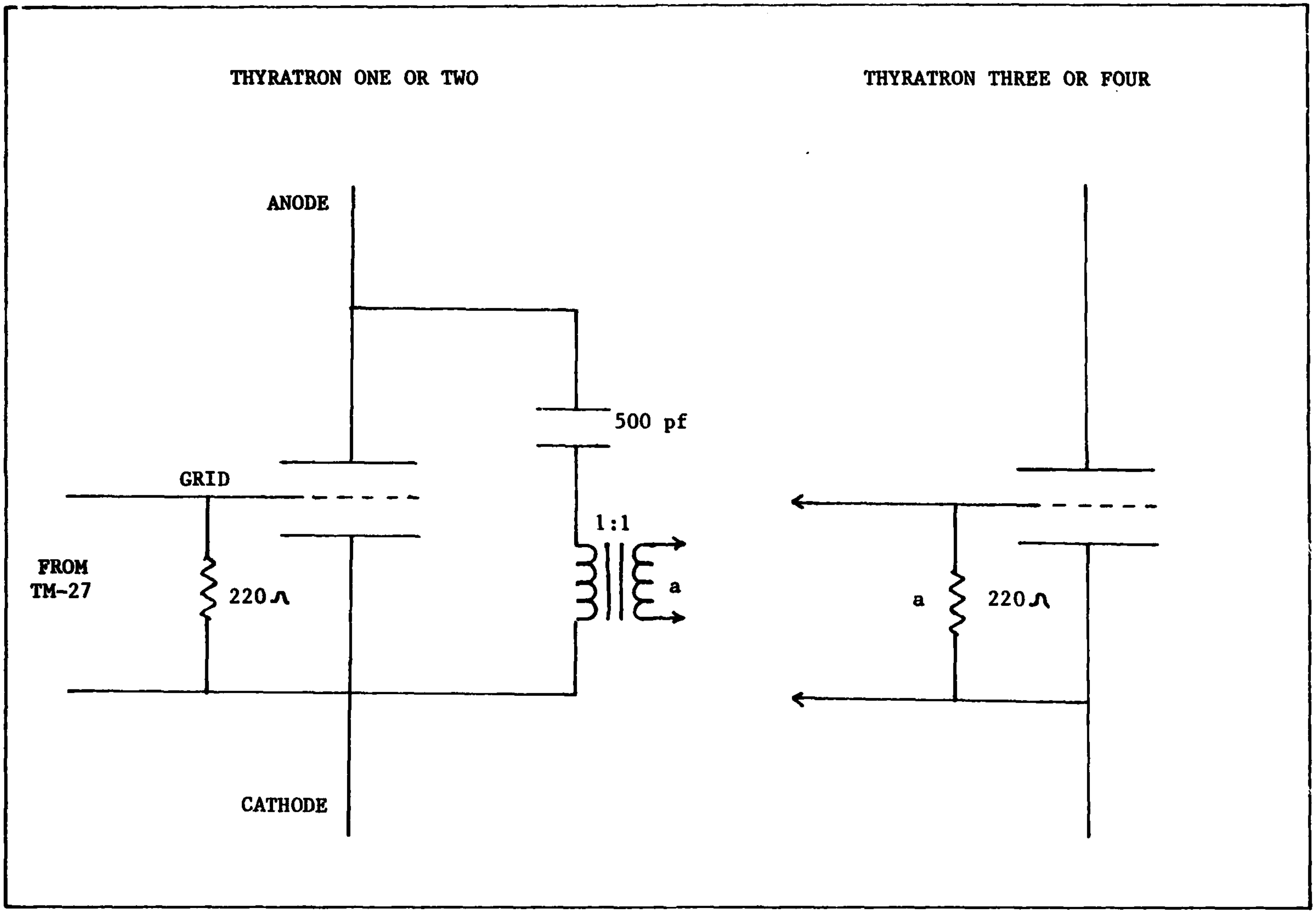

Figure C-1. Original Trigger Circuit

TABLE C-I

Effects of Trigger Capacitance

Capacitance	Effect
1000 pF	None
250 pF	None
125 pF	Slight deterioration of output pulse. Slight increase in tubes' three and four anode voltage spike.
55 pF	Further deterioration of output pulse. Anode spikes on tubes three and four increased.

Variations in Transformer Construction

The turns ratio of the transformer shown in Figure C-1 was varied to determine its effect on the time delay between firing of the Nth stage and the N+2 stage. The same transformer core was used in all cases.

Altering the turns ratio from 1:1 to 2:1 had no observable effect. The time difference between firings of tubes one and three was 70 ns, as was the difference between tubes two and four.

Making the turns ratio 1:2 had an effect on the time delay between thyratron firings. The time difference between tubes two and four was reduced to 60 ns. The time between firings of tubes one and three was reduced to 65 ns.

Conclusion

The trigger circuit using a capacitance of 500 pF and a transformer turns ratio of 1:2 gave the best performance in the internal triggering four-stage Marx.

Vita

Craig Lee Kimberlin was born on 5 February 1953 in Kansas City, Missouri, where he graduated from Northeast High School. He enlisted in the Air Force in 1972 and was discharged in 1974 to attend college in the Airman Scholorship and Commissioning Program. Upon graduation from the University of Missouri, Columbia with a Bachelor of Science in Electrical Engineering he was assigned to the Communications Security Center as a project engineer. In June 1980 he entered the School of Engineering, Air Force Institute of Technology.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFIT/GE/EE/81D-31	2. GOVT ACCESSION NO. AD-A115 580	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) INTERNAL TRIGGERING MARX GENERATOR USING HYDROGEN THYRATRONS		5. TYPE OF REPORT & PERIOD COVERED MS Thesis
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Craig L. Kimberlin 1LT, USAF; Randy L. Lundberg CPT, CE USA		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Institute of Technology (AFIT-EN) Wright-Patterson AFB, Ohio 45433		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS BEAM, PLASMA and DISPLAY DIVISION ATTN: DELET-BG ERADCOM FT. MONMOUTH, NJ 07703		12. REPORT DATE December 1981
		13. NUMBER OF PAGES 71
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

15 APR 1982

18. SUPPLEMENTARY NOTES

Approved for public release; IAW AFR 190-17

Lynn E. Wolaver

~~Frederic Lynch, MAJ,~~ USAF
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Dean for Research and Professional Development
Air Force Institute of Technology (ATC)
Wright-Patterson AFB, OH 45433

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Hydrogen Thyratron
Marx Generator
Internal Triggering Marx

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Operation of a Marx generator using hydrogen thyratrons as switches, with switches in upper stages of the Marx triggered by a signal derived from lower stages (internal triggering) was investigated. The Marx was in a negative output configuration. Triode, 8613, thyratrons were used with 175 nanosecond risetime, five section, E-star (E*) configured pulse forming networks (PFN's) as energy storage elements. Timing requirements and erection diagnostics were determined using a two-stage Marx, with both stages triggered from separate external sources (manual triggering). An attempt to trigger the second (N+1) stage from a signal

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) in the first (Nth) stage was unsuccessful because of long tube turn-on times. A three-stage Marx was examined, with all stages triggered manually, to confirm timing requirements. Triggering the third (N+2) stage from a signal in the first (Nth) stage, with stages one and two externally triggered, was successful. Triggering the N+2 stage from the Nth stage using a four-stage Marx was successful. The investigation showed the amplitude of the voltage spike, on the last stage anode, and the output pulse shape to be a function of the trigger timing between stages. Output pulse risetime was about 57% of the PFN's risetime.

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